JOURNAL OF THE
SOCIETY OF
MOTION PICTURE
AND
TELEVISION
ENGINEERS

Stereophonic Principles

Photographic Sharpness Evaluation

High-Speed Photography: Random Picture Spacing; in Chemical Industry; 35mm Full-Frame Camera

Primary Color Filters

35mm Stereo Camera

16mm Optical–Magnetic Projector

75th Semiannual Convention • May 3–7 • Washington, D.C.

NOVEMBER 1953

Society of Motion Picture and Television Engineers
JOURNAL VOL. 61 NOVEMBER 1953 NO. 5

Arthur C. Downes
Chairman, Board of Editors

Editor
Victor H. Allen

William H. Rivers
Chairman, Papers Committee

Basic Principles of Stereophonic Sound . . . . . William B. Snow 567

Psychometric Evaluation of the Sharpness of Photographic Reproductions
Robert N. Wolfe and Fred C. Eisen 590

Random Picture Spacing With Multiple Camera Installations . . . .
R. I. Wilkinson and H. G. Romig 605

High-Speed Photography in the Chemical Industry . . . . . .
W. O. S. Johnson 619

Full-Frame 35mm Fastax Camera . . . . . John H. Waddell 624

Primary Color Filters With Interference Films . . . . . .
H. H. Schroeder and A. F. Turner 628

A 35mm Stereo Cine Camera . . . . . C. E. Beachell 634

Projector for 16mm Optical and Magnetic Sound . . John A. Rodgers 642

German Test Film 652

American Standards 655
16mm 3000-Cycle Flutter Test Film, PH22.43-1953; 16mm Multifrequency Test Film, PH22.44-1953.

75th Convention Plans 658

74th Semiannual Convention . . 659

Book Review 661
The Theory of Stereoscopic Transmission and Its Application to the Motion Picture, by Raymond Spottiswoode and Nigel Spottiswoode, reviewed by John T. Rule.

New Members 663

New Products 665

Employment Service 666

Meetings 666

Subscription to nonmembers, $12.50 a year; to members, $6.25 a year, included in their annual membership dues; single copies, $1.50. Order from the Society's General Office. A 10% discount is allowed to accredited agencies on orders for subscriptions and single copies. Published monthly at Easton, Pa., by the Society of Motion Picture and Television Engineers, Inc. Publication Office, 20th & Northampton Sts., Easton, Pa. General and Editorial Office, 40 West 40th St., New York 18, N.Y. Entered as second-class matter January 15, 1930, at the Post Office at Easton, Pa., under the Act of March 3, 1879. Copyright, 1953, by the Society of Motion Picture and Television Engineers, Inc. Permission to republish material must be obtained in writing from the General Office of the Society. The Society is not responsible for statements of contributors.

PRINTED BY MACK PRINTING COMPANY, EASTON, PA.

Basic Principles of Stereophonic Sound

By WILLIAM B. SNOW

Stereophonic sound has become of vital importance to industry. The subject has been studied for many years, but the published material is scattered. This paper summarizes the fundamental theory underlying stereophonic sound so far as it has been published, and gives examples of how the theory is employed in representative practical situations. Fundamental differences between ordinary binaural listening and stereophony are pointed out, as well as similarities. It is shown that much qualitative but little quantitative information has been reported. Factors which aid some stereophonic effects are shown to be detrimental to others, and methods of minimizing the undesirable conditions are suggested. Applications to recording are discussed.

In 1941 K. de Boer wrote: "When the time comes to make use of stereophonic reproduction in the cinema, in broadcasting, etc., and the opinion becomes more and more general that the improvement in quality so obtained is worth the trouble, it will become necessary in the first place to find a process of making stereophonic records on a large scale."[6] Although even at that time stereophonic reproduction was far from new,[19-21] de Boer's enthusiasm for "making an orchestra plastically audible"[5] was shared by only a few. Now the time he forecast has finally come. Stereophonic sound has suddenly become of vital concern to the motion-picture and sound-recording industries, with multiple-channel recording the order of the day. This great upsurge of interest encouraged the preparation of this review of basic principles, and bibliography, as a guide for the large number of engineers who must quickly put this new technique into everyday use.

Stereophonic reproduction brings a truly remarkable increase in the realism of the sound and in the pleasure of listening to it. In one attempt to measure this quantitatively, reported by Fletcher,[2] the observers listened alternately to single-channel and stereophonic reproduction. In the stereophonic channels low-pass filters were inserted, while the single channel was maintained flat

Presented on October 5, 1953, at the Society's Convention at New York by William B. Snow, Consultant in Acoustics, 1011 Georgina Ave., Santa Monica, Calif.
(This paper was received September 2, 1953.)

to 15 kc. Half of the observers still preferred stereophonic reproduction when the low-pass cutoff was reduced to about 5 kc. However, this paper is concerned primarily with the mechanism of stereophonic sound rather than its advantages, which are now so well recognized. It is not the purpose here to repeat detailed discussions that can readily be found in the references. Such data are summarized, and additional interpretation is provided. The serious reader is strongly urged to study the references carefully; a good grounding in this complicated subject can be obtained only in this way.

DEFINITIONS

As in most new developments, differences in nomenclature have arisen which tend to obscure precise descriptions of systems. The words "binaural" and "stereophonic" are those most frequently used, but not with uniform meanings. This is not a new phenomenon. Alexander Graham Bell, writing in 1880,[1] referred to the "stereophonic phenomena of binaural audition," in describing experiments on the directional sense in hearing conducted with his newly invented telephone. The following definitions apply to the discussions of this paper and are limited to electro-acoustic sound-reproducing systems:

Binaural — A system employing two microphones, preferably in an artificial head, two independent amplifying channels, and two independent headphones for each observer. This duplicates normal listening.

Stereophonic — A system employing two or more microphones spaced in front of a pickup area, connected by independent amplifying channels to two or more loudspeakers spaced in front of a listening area. This creates the illusion of sounds having direction and depth in the area between the loudspeakers.

It is very important to distinguish between these systems. A binaural transmission system actually *duplicates* in the listener's ears the sounds he would hear at the pickup point, and except that he cannot turn the dummy head, gives full normal directional sense in all directions. A stereophonic system produces an abnormal sound pattern at the listener's ears which his hearing sense *interprets* as indicating direction in the limited space between the loudspeakers. It has been aptly said that the binaural system transports the listener to the original scene, whereas the stereophonic system transports the sound source to the listener's room.

ELECTRO-ACOUSTIC SOUND-REPRODUCING SYSTEMS

Outstanding differences and similarities of the various types of electro-acoustic reproducing systems are summarized in the chart of Fig. 1. The "System" names in column 1 conform to a uniform pattern and will be found in the literature, except "Monophonic" which is used for convenience as the opposite of stereophonic. "Equivalent Normal Experience" refers to the everyday hearing experience that most closely parallels listening over the systems in question. The next four columns are obvious. The column "Direct Sound Reproduction of Single Source Pulse" is probably the most important, since it gives the basic differences between the sound produced by the various systems. If a single sound pulse is produced by the source, this column gives the characteristics of the resulting *direct* sound pulses at the observer's ears. The direct sound is the initial sound transmitted directly from source

to observer by the shortest path, and arriving before any reflected sound arrives. It has been found that the direct sound carries the information, making angular perception possible, and it will be referred to frequently in what follows. Reverberant sound arrives from many angles and confuses the directional perception if too great in intensity. The "Remarks" column gives qualifying comments concerning the sound reproduction of each system. The reasoning behind these remarks is given in the body of the paper.

BINAURAL REPRODUCTION

Binaural reproduction as used herein means ordinary two-ear listening since the reproducing system transmits a faithful copy of the original sound to the listener's ears.

Angular Localization

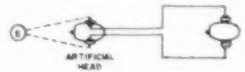
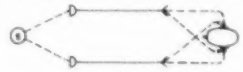
The properties of hearing which give the directional sense in binaural listening have been studied extensively.[11–18] For pure tones, angular localization is produced partially by phase differences at the two ears caused by the difference in distance from source to the ears as the source angle changes. The phase effect becomes ambiguous somewhat above 1000 cycles because at short wavelengths more than one angle results in the same phase difference. However, in the higher-frequency region intensity differences produced by the diffraction or sound-shadow effects of the head and external ears become great enough to give angular localization.

The great majority of sounds are not pure tones, but complex. For complex sounds the equivalent effects are arrival time and quality difference. A complex wave pulse has an initial wavefront which arrives at the near ear a short time before it arrives at the far ear. It is this small time difference which is used by the hearing sense to determine small angular variations, particularly for sounds near the median plane (straight ahead). It is characteristic to turn toward a source to locate it with maximum precision, and for impulsive sounds such as speech or clicks, differences as small as 1° to 2° can be perceived. These angles correspond to arrival-time differences of about 10 to 20 μsec, and the maximum possible difference, for a source in line with the two ears, is only about .700 μsec. The loudness differences at such small angles are negligible and it must be assumed that the arrival-time differences give the localization clues. On the other hand, it is not possible for the mechanism of a *single* ear to distinguish such short time intervals[17]; this "decoding" of the arrival time differences must be accomplished by the brain.

The arrival-time effect is aided by the quality differences at the ears caused by sound diffraction.[22] Quality difference is another way of saying that a change in waveshape is produced. The intensity differences due to diffraction are functions of frequency and cause a complex sound to have a different frequency-intensity composition or quality at each ear. It is undoubtedly this effect which removes ambiguities in direction which would result from arrival time alone, because the diffraction effects are so complicated that a given quality difference can correspond only to one direction. Quality differences also change most rapidly near the median direction; consequently, angular localization is much less precise at the side than in front or back.

Changes in both arrival time and quality are relatively small as a source is elevated in front of an observer. Therefore the ability to distinguish angle in the vertical direction is relatively poor.

Fig. 1. Electro-acoustic sound reproducing systems.

Type of system	Equivalent normal experience	Pickup	Number of channels	Reproducer	Symbolic schematic	Direct sound reproduction of single source pulse	Remarks
Monaural	One ear plugged	1 Microphone	1	1 Headphone		1 Pulse to 1 ear	Only partial equivalence, as directional effects are not duplicated
Diotic	Sound source in median plane only	1 Microphone	1	2 Headphones		1 Pulse to each ear 0 time difference No quality difference	Only partial, as directional effects of elevation not duplicated. No directional effect of room reverberation Qualitatively much superior to monaural
Binaural	Normal listening, head stationary	2 Microphones in artificial head	2	2 Headphones		1 Pulse to each ear 0 to 0.6 msec time difference Normal quality differences	Directional and quality effects of normal listening in *pickup room duplicated* throughout *360° sphere* *No* listening room effects Observer cannot turn to face virtual source
"Monophonic" ordinary loudspeaker	Sound coming through a hole in a wall	1 Microphone	1	1 Loudspeaker		1 Pulse to each ear 0 time differences No quality differences	Both ears used—binaural listening to a single fixed sound source position Composite of pickup and listening room acoustics Listening room reverberation has directivity Represents widely spaced "effects" loudspeakers
Stereophonic	None	2 or more microphones	2 or more	2 or more loudspeakers		2 or more pulses to *each* ear 0 to 30+ msec time differences Complex quality differences	Depends on fusion of multiple pulses by ears Directional and quality effects of normal listening *simulated* for a *limited angular area* appearing as part of *listening room* 360° simulation would require a large number of channels Composite of pickup and listening room acoustics Reverberation has partial directivity in pickup room, full directivity in listening room Observer can turn to face virtual source Time differences from both source and observer positions

Pseudo or bridged stereophonic	None	1 Microphone	2 or more	2 or more loudspeakers		2 or more pulses to *each* ear 0 to 20+ msec time differences Small quality differences

Single source only
Many properties identical with true stereophonic system
Time differences *only* from observer position, and detrimental
Identical signal-reverberation pattern from each loudspeaker
Identical quality from each loudspeaker
Many other bridged combinations possible

The statement is made in Fig. 1 that the observer cannot turn to face the source. While systems have been constructed with servo connections between observer and dummy,[7] thereby improving localization, this is not practicable for a system used with multiple observers, or with a recording link.

Depth Localization

Perceiving the position of a sound source in space involves the determination of distance as well as angle. The ear has no mechanism corresponding to that of the eye for converging on the source, and must depend on less definite clues. In the absence of reverberation, the only information given is intensity and quality. From past experience the ear can form an approximate idea of distance from its interpretation of the *absolute* loudness of a sound, and from its judgment of quality differences produced by atmospheric absorption. These comparisons are made with a mental image of what the sound should be. In the presence of reverberation,[23] the ear can judge distance based on the ratio of direct to reverberant sound. Since neither of these methods is precise, judgment of distance is much less accurate than perception of angle. Probably everyone has had the experience of badly misjudging the distance of a sound heard for the first time, whereas no difficulty was experienced in determining its direction.

Fundamental Difference from Stereophonic Sound

This discussion of the determining phyrical factors underlying ordinary binaural hearing has been given at some length to lay a foundation for the discussion of those underlying stereophonic reproduction. There are basic differences which have been almost universally overlooked. When this confusion is cleared up, stereophonic reproduction can be used with much greater ease and satisfaction.

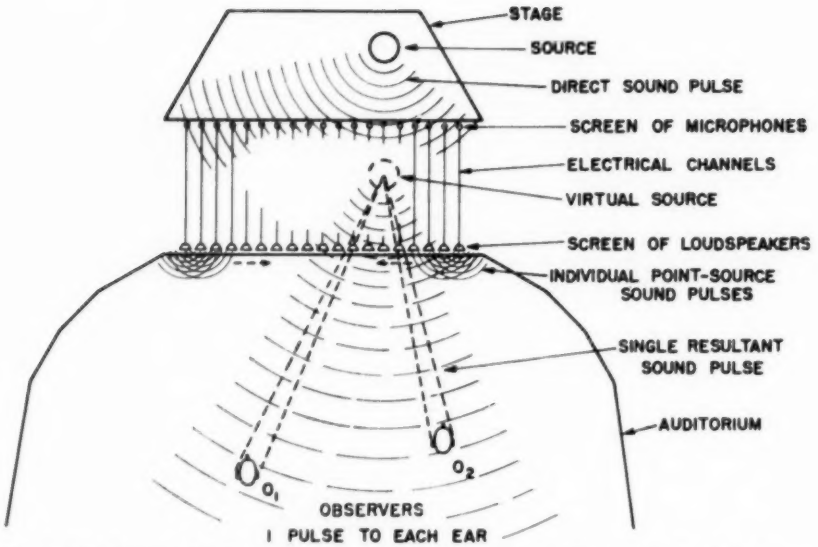


Fig. 2. Ideal stereophonic system. A very large number of very small microphones and loudspeakers would give a perfect reproduction of the original sound.

STEREOPHONIC REPRODUCTION

Fundamental Process

Publications. Good summaries of stereophonic sound are given by Frayne and Wolfe[24] and Knudsen and Harris.[25] Only a few reports on the fundamental principles of stereophonic reproduction have appeared in the literature[4,8,9,17,27,30] and these do not discuss identical operating systems. The Bell System tests and those at Twentieth Century-Fox Studios were made with widely spaced microphones, whereas scientists of the Philips Company employed closely spaced microphones, usually in an artificial head. It is unfortunate that additional fundamental tests made at Bell Telephone Laboratories were never reported in technical journals because of the press of other work and the advent of the War. In spite of this, we believe it is possible to understand the principles qualitatively, if not fully on a quantitative basis, and that the results so far published are for the most part consistent.

Screen Analogy. It has become customary to describe stereophonic reproduction as follows: A screen consisting of an extremely large number of extremely small microphones is hung in front of the sound source. Each microphone is connected to a corresponding extremely small loudspeaker in a screen of loudspeakers hung before the audience. Then the sound projected at the audience will be a faithful copy of the original sound and an observer will hear the sound in true auditory perspective. It is then stated that such an impractically large number of channels is not needed and that good auditory perspective can be achieved with only two or three channels. These are true statements, and the natural inference from their juxtaposition is that far less than faithful "space" reproduction of sound will give localization by ordinary binaural mechanisms. When we proposed this theory early in

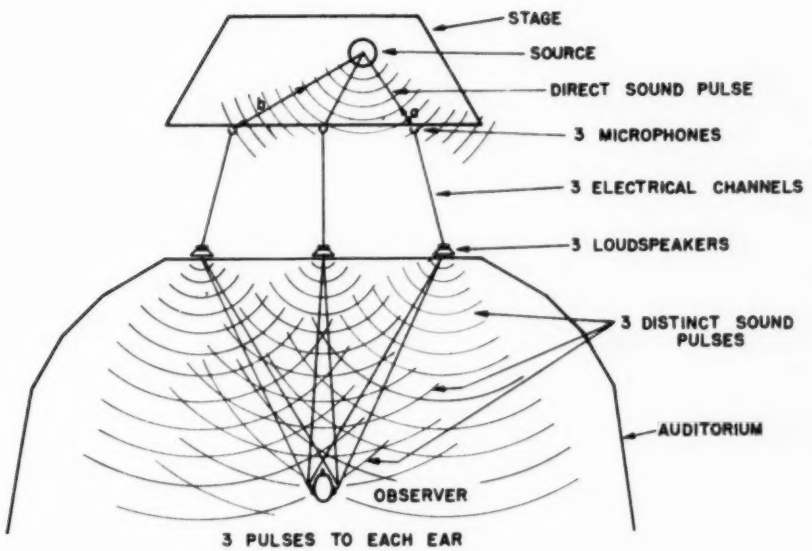


Fig. 3. Actual 3-channel stereophonic system. A practical stereophonic system gives a multiple reproduction of the original sound which the observer interprets as coming from a single source.

our studies of stereophonic phenomena, we realized that there were fundamental differences which were not fully understood, and pointed out the multiple source effect in connection with our loudness calculations.[26,27] Apparently this has not been sufficiently emphasized. The experience of the intervening twenty years has convinced this writer that this natural inference is mistaken, and has caused the confusion postulated in the previous section.

The myriad loudspeakers of the screen, acting as point sources of sound identical with the sounds heard by the microphones, would project a true copy of the original sound into the listening area. The observer *would* then employ ordinary binaural listening, and his ears would be stimulated by sounds *identical* to those he would have heard coming from the original sound source. As shown in Fig. 1, this means one direct-sound pulse to each ear for a single pulse from the source. The phenomena are illustrated schematically in Fig. 2.

Operating Conditions — Illusion Created. Figure 3 illustrates the conditions for a typical setup where only three channels are used. This arrangement does indeed give good auditory perspective, but what has not been generally appreciated is that conditions are now so different from the impractical "infinite screen" setup that a different hearing mechanism is used by the brain. Each individual loudspeaker sends a pulse to the observer. He therefore receives *three* faithful copies of the sound at *each* ear in rapid succession. The time differences between these pulses are too short to allow the ear to distinguish them as separate; consequently the hearing mechanism fuses them[17] into an *illusion* of a single sound pulse coming from a virtual sound source located somewhere in the space between the outer loudspeakers. The

time differences are short, but still long compared to the maximum of 700 μsec to which the ears are accustomed in normal listening. Thus this type of listening falls outside of normal experience, but fortunately the brain is able to form a single concise impression from what might be expected to be a confusing set of signals sent by the ears.

The closest parallel is reverberation. But while there are distinct similarities, the three direct-sound pulses arrive ahead of any reflections other than the floor reflections which do not have individual directivity. In addition, they are separate and distinct, of high fidelity, and in a compact directive pattern. The reverberation follows as a "smear" of echoes of random directivity, and does not create a virtual source illusion.

The problem, then, in stereophonic reproduction is to produce multiple sound images at the ears of the observer which will fuse in such a way as to give the desired *illusion* of sound origin.

Angular Perception

Intensity Differences. What are the characteristics of the direct-sound pulses which cause them to give the observer the sensation of angular localization of the virtual source? The most obvious difference is intensity of sound projected by the several loudspeakers. These differences are caused by the varying distances of the source from the various microphones. When the source moves close to a microphone the output of the corresponding loudspeaker is greater than that of the other loudspeakers, and localization tends in its direction. The virtual source therefore moves in the same direction as the real source, and with proper system design can be made to have essentially proportional movement. In the original paper[27] Dr. Steinberg and this writer discussed this in detail and proposed a theory for the effect of these intensity differences, based upon the total loudness that would be produced in each ear by the total direct sound from all loudspeakers, taking into account the directivity of hearing caused by the shape of the head. While the agreement between the theory and experimental results was by no means perfect and the differences were pointed out, the theory did appear to account for the main effect. This theory has been questioned by other experimenters, principally, it is believed, because of the common confusion between the mechanisms of ordinary binaural hearing and stereophonic hearing which the discussion above should have now dispelled.

While a true understanding of the process is highly desirable, for the purposes of this paper it is not necessary to be certain of the precise physiological and psychological mechanisms involved. It is well established that intensity differences in the channels are an extremely important contributor to angular perception. With positions of source and observer fixed so that all other factors are constant, variation of the gain controls in the channels can shift the virtual source to any angular position in the reproducing area. This is true for any combination of source and observer positions. In practice this is important because gain is easily controlled, to correct faults in pickup, or to enhance angular movement. The bridged-microphone system of Fig. 1 operates on this basis, since the only differences that can be given the loudspeaker outputs must be obtained from electrical controls in the channels. As this is written, many pictures are being made "stereophonic" by the use of volume controls in bridged channels from sound tracks originally recorded for single channel or "monophonic" reproduction. The pseudo-stereophonic system has its place; but it is not a satisfactory substitute for a real stereophonic pickup. It does not have the benefit of the other aids to angular or depth perception described below; and

in particular it can be used on only a single source at one time, so that an individual source and "pan-pot" must be supplied for each sound.

Quality Differences. If the microphones have varying directivity with frequency, there are quality differences as well as intensity differences in the channels as the source moves. Angular localization is definitely affected by this. It has been found that the higher frequencies, where the head has relatively high directivity, contribute most to stereophonic localization. Localization tends toward the loudspeaker giving greatest high-frequency output, if the overall loudness is the same.

The very low frequencies contribute essentially nothing to stereophonic localization. For example, poor localization results if 1000-cycle low-pass filters are inserted, and no difference in localization is produced by eliminating frequencies below 300 cycles. It has been found[4,10,40] that much of the stereophonic effect is preserved if low frequencies are reproduced from only one low-frequency unit and side channels reproducing only frequencies above 300 cycles are employed. This is of great practical value for economical stereophonic reproduction such as home music systems. For the flexibility and high fidelity demanded by motion-picture and auditorium reproduction its use appears questionable until a great deal more study of it has been reported. The Philips tests[10] employed microphones a small distance apart; with widely spaced microphones characterizing the practice in this country serious pickup difficulties can be foreseen, as well as "crossover" complications in the loudspeaker systems. For "special effects loudspeakers," however, the low frequencies do not appear necessary if the main object is to obtain localization.

Arrival-Time Differences. Another phenomenon affecting angular localization is the change in arrival time of the direct-sound pulses from the several loudspeakers as the source moves upon the stage. These differences were mentioned above, and were shown to be considerably greater than those ordinarily encountered in simple binaural hearing. For example, in Fig. 3 the right and left channels reproduce sound pulses from the source later than the center channel by time intervals corresponding to distances *a* and *b*, respectively. The observer does not recognize the three pulses as distinct. However, it has been shown[17,41] that localization tends towards the loudspeaker which reproduces the earliest pulse. These effects have been called "Fusion" and the "Precedence Effect" by the authors of Ref. 17, who give a clear and detailed discussion of their relation to stereophonic reproduction. Qualitatively their discussion applies to stereophonic reproduction in general, but the precise data on precedence is limited to time differences of 2 msec or less, whereas common stereophonic conditions produce differences much greater than this. The following qualitative statements are deduced from this writer's own experience:

(a) The effect of arrival time is to make localization tend toward the loudspeaker from which the pulse arrives first.

(b) This effect is strong for small differences, say up to 3 or 4 msec, and tends to become weaker for greater time differences.

(c) The effect is relatively independent of where the differences are produced, whether on the pickup stage, in the listening room, or in the reproducing channels. Therefore differences in one section add to those in another, or can be made to compensate each other.

(d) These effects can be largely compensated by intensity or quality differences inserted in the channels, for any one observing position.

This effect acts to reinforce the

intensity effect for movement on the pickup stage. As a source moves toward a microphone the arrival time is advanced at the same time that intensity is increased. This is one of the important factors not duplicated by the bridged system. An interesting application is described by Grignon[39] in the triangular microphone arrangement for assuring center localization while maintaining stereophonic quality for a soloist or small source. Here the small advance of arrival time on the center microphone holds localization to the corresponding loudspeaker.

Reverberation. A fourth factor that might contribute to angular localization is ratio of direct to reverberant sound. Experience has shown, however, that it plays a very minor part in angular localization.

Dynamic Localization. Moir and Leslie[18] provide a very interesting observation on localization, as follows: "...dynamic localization of a source appears to be appreciably more accurate than is shown by the data obtained from localization tests on a stationary source. This applies to all variations of two- and three-channel systems that we have compared."

Depth Perception

Depth perception in stereophonic reproduction is controlled by essentially the same factors as in ordinary binaural listening described above, viz.: absolute intensity, quality, and ratio of direct to reverberant sound.[27] As the sound intensity decreases, the impression is produced of the sound moving away. The same illusion accompanies a relative loss of high frequencies. The most important contributor to the feeling of depth, however, is change in the ratio of direct to reverberant sound on the pickup stage. As the reverberant energy becomes more prominent, the source appears to recede on the virtual stage. In practice the microphones are closer to the sound sources than listeners would be, and changes in direct-to-reverberant sound ratio can be heightened to give more definite impressions of depth on a virtual stage than are created on a real stage. This can be seen in Fig. 1 of Ref. 27. As in ordinary listening, however, depth localization is less precise than angular localization.

Effect of Observer Position

Up to this point, for the sake of simplicity, the paper has been written as if all observing positions were equally good. Actually this is far from the case, as all experimenters have pointed out. From the standpoint of the practical use of stereophonic reproduction in the theater, this is a truly serious problem. Here the very factors which produce the stereophonic effect prove a disadvantage in some aspects, and measures must be taken to compensate them.

Source Position Shift as Observer Moves. The effects so far described characterize listening at the position of Fig. 3, or other listening positions on the center line where the distances to the side loudspeakers are equal. They also apply to other observing positions qualitatively, but as the observer moves away from the center large shifts of virtual source position may occur. The stereophonic feeling of spaciousness is preserved, and virtual sources continue to move, but they are not localized at the same place on the stage by all listeners as they would be on a real stage.

Figure 4 illustrates what is happening, for a source at center of the pickup stage, and a typical setup. Observer 1 receives identical direct sound pulses from the two side channels. Even here, however, the center-channel sound arrives slightly ahead of that from the sides, and at greater amplitude. In practice, the center channel is operated at lower gain than the side channels to correct for this.

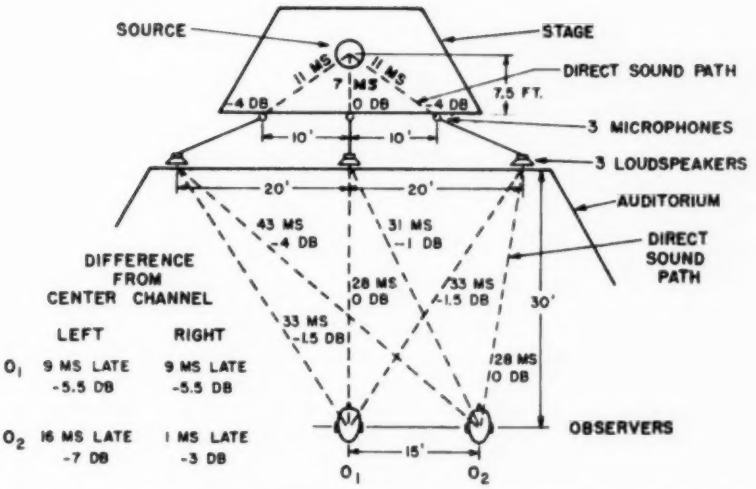


Fig. 4. Effect of changing listening location. As the observer moves away from the center-line of the auditorium the sound from the "near" loudspeaker increases in intensity and decreases in relative arrival time, making the virtual source shift in the same direction.

Observer 2 at the right receives pulses from the three loudspeakers with the relative times and intensity levels shown. It is seen that the righthand loudspeaker now contributes both a more intense signal and an earlier signal than before; and both of these effects are known to make localization tend in its direction. This is indeed the case, and as the observer moves to the right the virtual source position moves in the same direction. Note that the differences in time are several milliseconds. Qualitatively (again based upon personal experience) it is found that a considerable shift takes place for small observer deviations from the center, where relative intensity changes are small. These must be ascribed to changes in arrival time. For any given observer position these shifts can be compensated by changes in channel gains, and appear to become relatively constant at anything over a few milliseconds. Obviously the effects of intensity increase can be overcome by unbalancing the channel gains.

Methods of Reducing Shifts. The patent of Ref. 41 contains a suggested method of alleviating these troubles. The loudspeakers would be so designed as to project a delayed signal and one of reduced intensity in the forward direction compared to the side directions. This would tend to equalize conditions for the various observing positions.

Suppose that observer 2 remains at the right while the source moves to the left. The intensity increases in the left channel, but more important the arrival times become more nearly equalized, and the virtual source moves toward the left. Only the intensity change is duplicated in the bridged channel, so that there is definite advantage in the real system considering all observing positions. If the source moves to the right, the arrival time disparity is aggravated; but since there appears to be a limit to the effect of arrival time this negative effect is smaller than the positive advantage for movement to the left, and an overall gain results.

If the observer turns his head to follow movement of the virtual source, the effect is to oppose the movement, since the ear on the side of the head in the direction of movement in effect turns away from the loudspeaker of increasing intensity, and the opposite ear turns toward the loudspeaker of decreasing intensity. Since the sound tends to move "too fast" toward the microphone being approached because of the combined effects of intensity and arrival time, this is an advantageous compensating factor, considering all seats in the auditorium.

APPLICATION OF BASIC PRINCIPLES

The practical art of applying stereophonic reproduction for public use is now building up rapidly, and many papers may be expected in the future. The various references contain data on the small number of tests made previous to 1952, notably Ref. 39 in which Grignon describes tests specifically designed to determine techniques applicable to motion-picture production. The present paper is concerned primarily with the underlying principles, but it seems useful to give some illustrative examples of how they are used. These examples are primarily of situations with which the author has had personal experience.

Number of Channels

The number of channels will depend upon the size of the stage and listening rooms, and the precision in localization desired. Two channels give a large measure of the spacious effect desired for stereophonic reproduction, and will give fairly accurate localization for a small stage. Such a system on an ordinary-sized stage will give quite different localization impressions to observers in different parts of the auditorium, and is apt to suffer from the "hole-in-the-center" effect where all sounds at center stage seem to recede toward the back. Nevertheless, for a use such as rendition of music in the home, where economy is required and accurate placement of sources is not of great importance if the feeling of separation of sources is preserved, two-channel reproduction is of real importance.

That this is true is borne out by the current sponsored programs being broadcast by radio stations in various parts of the country using the FM transmitter for one channel and the AM transmitter for the other. Experience with this service in the writer's home has demonstrated the great increase in enjoyment it provides. Various methods for utilizing a single carrier for this type of broadcasting have been proposed,[18,40,42] using upper and lower sidebands separately, simultaneous AM and FM modulation, and modulating one channel on a subcarrier which is then modulated with the other channel on a regular FM transmitter. For such service the idea of supplying only one low-frequency loudspeaker appears important. It is well to recognize that a poor crosstalk ratio between channels in such a stereophonic system is not serious, because the relative intensity levels in the two channels never become greatly different. Thus systems which could not be considered for separate programs may be usable for stereophonic reproduction.

Three channels appear to be a good economic choice for ordinary stages and auditoriums. Good accuracy of localization can be achieved for favorable observing positions, with reasonable results at other seating locations. The center channel is a great aid for solo and close-up work, as well as removing the "hole-in-the-center" effect mentioned above. For unusually wide stages, additional channels have been found necessary.[43,44] At present it may be taken as a rule of thumb that additional channels should be considered

when stage dimensions require channels spaced more than 25 ft on centers.

Loudspeakers

Placement. Loudspeaker placement is straightforward if considered for sound alone. The outside loudspeakers are placed at the outside edges of the space considered the reproducing stage, since sound cannot be made to travel past the outside speakers. The center, or other loudspeakers are placed at uniform spacing across the stage. It was stated that the close microphone position ordinarily used makes it possible to enhance depth effects. The source can therefore be made to appear in front of the loudspeakers, and they may be placed a few feet back of the front of the stage. In the Bell System demonstration at Carnegie Hall in 1940, the outside loudspeakers were spaced 40 ft on centers, and the front of each loudspeaker was 11 ft back of the decorative sound-transparent front curtain.[35] This curtain was illuminated in various simple color patterns during the performance, an artifice which adds enjoyment when no picture accompanies the sound.

For sound-picture reproduction, the effect of the picture is great, and the precision of localization required is smaller. If the sound tends to be in the region of the visible source, it will be localized there. Consequently here it *is* possible to create the illusion of sound outside the farthest loudspeaker.

When the stereophonic system is used for sound reinforcement serious difficulty may be experienced in placing the loudspeakers where they will not obstruct the view. Fortunately here, also, the source is visible. In addition, it was shown that localization in the vertical plane is poor. The loudspeakers can therefore be placed above or below the stage level without loss of illusion provided high fidelity of reproduction is maintained. It is also sometimes possible to use a smaller loudspeaker in the central positions, without full low-frequency response, to give proper localization. One of the most successful stereophonic reinforcement systems was tested in the Hollywood Bowl in 1936,[45] where the loudspeakers were mounted on a platform 45 ft above the stage level. The system supplied almost uniform sound level throughout the seating area, and considerable amplification even for the closest seats. Nevertheless the illusion that the sound came directly from the orchestra in the shell was excellent. To preserve a good illusion the loudspeakers should have approximately the same spacing as the channel microphones.

Characteristics. Since the illusion is caused by the receipt of multiple sound pulses, and in view of the observer-position effects discussed above, it is important that the loudspeakers give uniform angular coverage of the whole seating area. Actually, according to the disclosure of Ref. 41, greater energy should be supplied to seats at the side than to those in front of a loudspeaker, the inverse of the ordinary loudspeaker directional characteristic. Some toeing-in of the outside loudspeakers will help the average situation. In addition to these factors, de Boer[4] also recommends minimizing sound projection to areas outside the audience to reduce wall reflections, and maintaining the quality of the several channels above 300 cycles as alike as possible. Quality differences will be interpreted in the stereophonic illusion as differences in direction.

Bridged Loudspeakers. It is possible to bridge a center loudspeaker across the outside channels, which has the effect of reducing the apparent stage width.[6,27] This would be useful if it were impossible to place the side loudspeakers as close together as desired. It would be subject to the limitations of bridged systems already pointed out.

Microphones

Placement. Microphone placement may be simple or complicated, depending on the application. From what has been said, it will be evident that creating the stereophonic illusion is a compromise between favorable and unfavorable factors, and microphone placement and movement can be used to advantage in effecting this compromise. Since the illusion depends upon differences in intensity and arrival time at the microphones, and change in ratio of reverberant to direct sound, the microphones must be placed close enough to the sources to create these differences. This means that each microphone "covers" only part of the stage and will be closer than fixed microphones placed for single pickup. If pickup of action is necessary in a room where ordinary reverberation times obtain, the necessity of close pickup is apt to accentuate depth effect, and require a small stage area. Then dimensions are multiplied if a larger reproducing stage is used, and the speed of movement on the pickup stage must be slowed by an appropriate factor. Conversely, if the action demands a large stage, special microphone-handling techniques such as those described by Grignon[39] will probably be necessary. A good combination is a dead stage in which a set of the size that will accommodate the action can be constructed with the proper combination of "flats" to give a reflected sound content that will produce the desired depth illusion.

The motion-picture industry is rapidly developing the art of microphone movement for stereophonic recording where action and movement of camera are all-important. For other stereophonic pickup, such as music, radio plays or sound reinforcement, fixed microphone positions aided by some mixed-in special pickups will usually suffice. The regular microphones are deployed in front of the stage. If all action is at front stage, the outside microphones should be at the outside edges. However, to secure the illusion of action on a rectangular stage requires a greater stage width at the rear line than at the front (Fig. 6 in Ref. 27), and some compromise must be made; so the side microphones are usually placed somewhat inside the edges. This is particularly true of a two-channel system where a compromise between "hole-in-the-center" sound and well-spread sound must be effected. In this connection, a bridged center microphone is frequently used and does fill up the hole for center observing positions. However, it obtains this effect by adding sound to the side channels at advanced arrival time, thus aggravating the shift of the virtual source as the observer moves to the side of the auditorium.

After considerable experimentation, the microphones for the Philadelphia Orchestra recordings demonstrated by the Bell System in 1940 were suspended 10 ft above the stage and 5 ft inside the front row of musicians. The orchestra width was about 40 ft and the outside microphones were 28 ft apart. For small stages with actors, good results were obtained with a 12 ft square stage in a very dead room, using two microphones 9 ft apart and 5 ft from the front of the stage. In a rather reverberant medium-sized room a stage 15 ft wide by 6 ft deep, using three channels, with the microphones on 6-ft centers and 4 ft from the front line, proved satisfactory. In this case, note the shallow depth dictated by the reverberation in the room.

Directivity. Directive microphones can frequently be used to advantage. Since to produce an angular illusion it is necessary to generate intensity differences in the channels, a study of the geometry will show that greater movement is required at the rear of the pickup stage than at the front to produce a given angular impression. If the microphones are directive, greater intensity

changes will occur as a source moves across the stage from the lobe of one microphone into that of another, and the rear line will be shortened. At the front line the directivity effect may be so great that the sound appears to recede between microphones. Experiment has shown that with moderate directivity, and by toeing in the lobes of the side microphones somewhat, an advantageous compromise between these two effects can be made and better overall coverage of a rectangular stage obtained.

This effect may be obtained with microphones of uniform directive properties, such as the cardioid types, or with the directivity only at high frequencies characteristic of a relatively large condenser or dynamic microphone at normal incidence. The latter will give accentuated directional effects with less change in overall loudness. Here directional effects are really quality changes. While in monophonic reproduction these quality changes would be objectionable, in stereophonic work the listener's fused impression consists of the contribution from several sources and the source is always in the direct lobe of one microphone. If the normal-incidence characteristic of the microphone is considered in overall system performance, the fidelity will remain high from all source positions.

The elimination of pickup from behind the microphones is a definite advantage in most cases. Obviously it eliminates noise. But it also eliminates part of the reverberation, and since most stages have more than the desired reverberation ratio for the physical depth, this is an advantage.

Reverberation. A pickup problem which has received little study as yet involves the adaptation of the reproduction to the listening room. The concept for reproduction in a theater or concert hall appears straightforward. To get good localization requires close pickup, and therefore the radiated sound approaches in quality the direct sound that would have been projected into the theater by a live (if gargantuan-voiced) performance. The theater then applies its own acoustical characteristics to the sound. In broadcasting and phonograph reproduction, however, listening is usually done in small, rather heavily damped rooms, and monophonic microphone techniques have been worked out to give a pleasing amount of reverberation from the pickup stage. Without doubt, some way will have to be found to produce a similar effect in stereophonic reproduction with the closer pickup required.

Bridged Microphones. Since channels are expensive and the complications grow with greater numbers, it is tempting to use bridged microphones to simplify the system. If this technique is used with restraint to gain additional realism in reproduction, it can be extremely useful. If it is used in the hope that it will be a cheap way of duplicating the performance of a more elaborate system, the results are bound to be disappointing. The tests reported in Fig. 1 of our original article[27] demonstrate this and are worth careful study. Discussion offered above explains why such techniques cannot be expected to duplicate real stereophonic channels.

An example of a useful application of the bridged microphone is its use to emphasize a small group of instruments in an orchestra, when the overall pickup is satisfactory in other respects. This was employed in the Hollywood Bowl demonstration[45] where one extra microphone was used continuously on the right channel, and others were employed during special parts of the performance. In monophonic systems multiple microphone pickup often leads to poor fidelity because of cancellation between the signals from the microphones in specific frequency regions. In stereophonic

systems this effect is ameliorated because sound is fused from several sources.

When a solo instrument or voice is to be employed with an orchestra, separate pickup is very effective. The microphone should be arranged to pick up as little as possible of the orchestra, and the output should be mixed into the orchestra channels to give the localization desired. By far the best result will be obtained if the three-microphone triangular pickup described by Grignon[39] is used. The soloist will then be localized by substantially the whole audience at the desired location and the realism will be enhanced over a single microphone pickup.

Amplifiers

Amplifiers for use in stereophonic systems do not differ from those of monophonic systems except in number. The characteristics of the amplifiers in the various channels should be similar, and the gain should be stable so that no undesired level differences will occur. It is usually found desirable to have a ganged volume control which will adjust the overall level, and an individual control in each channel for balance or intentional unbalance settings. Similar provisions for quality-changing networks are desirable. If bridging systems are to be used proper networks and bridging amplifiers must be provided to insure that signals flow only in the desired directions, and inadvertent gain changes are not made during switching. It is also good practice to observe a poling convention throughout all channels, including the microphones and loudspeakers, although the channel spacings are so wide that only very low frequencies can be considered at other than random phase in one channel compared to another.

As a matter of economics, it is probably true that the added complication of stereophonic reproduction will be employed only for high-fidelity reproduction. Consequently the amplifier systems will require the same care in design and attention to detail that is required to secure high fidelity in monophonic systems.

APPLICATION TO RECORDING

The general principles of stereophonic sound apply to reproduction whether it is from recordings or from direct transmission by wire or radio. Recording has problems of flutter and maintenance of time differentials between channels peculiar to itself, and in general yields more severe technical problems in maintaining low noise and distortion. Yet it is certain that the great bulk of listening hours will be provided by recorded material. The effect of such distortions in stereophonic recording is therefore of great importance.

Distortion

The consensus of reported opinion in the literature is that stereophonic reproduction reduces the objectionableness of distortion and noise.[18] This unwieldy word is used because no test data are available to show whether the distortions become less detectable by the observer, or whether he is willing to overlook more distortion because of the increased pleasure of listening provided by stereophonic sound. Doubtless both reasons are true in part. The most outstanding example of the latter is the preference of observers for stereophonic sound, even though seriously degraded in frequency band.

Subtractive Type. It seems probable that distortions of a "subtractive" nature are actually less detectable. A dip in response of a single loudspeaker, or the equivalent caused by cancellation between two microphones on the same

channel, will not be so noticeable if sound contributions from other channels not so distorted are being fused with the distorted signal.

Flutter. By similar reasoning, it seems probable that flutter will not be as noticeable on stereophonic reproduction. It is well established[46] that small frequency variations in the signal are turned into much larger amplitude modulations by the sharp resonances of the listening auditorium, and these are detected by the ear. Each channel will excite a different resonant pattern in the room. The fusion effect should therefore reduce the resultant modulation at the ear, with consequent reduction in flutter sensitivity.

Additive Type. It does not seem likely that the actual detectability of "additive" effects such as noise and distortion-product frequencies would be decreased by stereophonic reproduction, but their degrading effect does seem to be lessened. In monophonic reproduction any noise (distortion products are equivalent to noise) competes directly with the signal for attention whereas in stereophonic reproduction the directional illusion separates noises and program in space and allows the observer to concentrate more on desired sounds. Moir and Leslie[18] report a 12-db improvement in signal-to-noise ratio "due to the ears' steerable directivity pattern."

Channel Differences

Quality. For ideal results the quality of the various channels should be identical. Differences in quality will show up as differences from desired localization. On the other hand, a stereophonic effect will be preserved even with fairly large differences in quality. Consequently, in practical operation the attention now given to maintenance of uniform frequency response in high-fidelity monophonic systems will be adequate for the channels of stereophonic recording systems.

Level. The level difference between channels should be kept small, but the requirement does not seem inordinately difficult. A 2-db unbalance between the channels of a two-channel system — the most critical case — would shift the virtual source about 4 ft across a 45-ft stage.

Time. The requirement of time-identity of scanning position for the channels is considerably more stringent for true binaural than for stereophonic reproduction. Fifty microseconds difference would cause a 5° shift in binaural localization, corresponding to 0.7 mils misalignment for 15 ips track speed. However, for a two-channel stereophonic system a severe requirement might be 1 msec, corresponding to 15 mils misalignment for 15 ips track speed. This amount, equivalent to approximately 1-ft distance difference, would correspond to an actor moving from one side of a chair to the other, or to an auditor shifting from one seat to the next in the theater.

Dubbing

In the process of preparing a recording for release, a very important function is dubbing-in sound effects and music, or re-recording with altered quality or balance. In stereophonic recording there is the added requirement of proper position of the sound. When a single source must be given position, use is made of a bridged system and a "pan-pot." This is an arrangement of attenuators on a common control which will feed to each channel an intensity simulating the intensity it would have received if the original recording had been made with multiple microphones. The characteristic of the instrument built for the Auditory Perspective demonstrations of January 1934 is

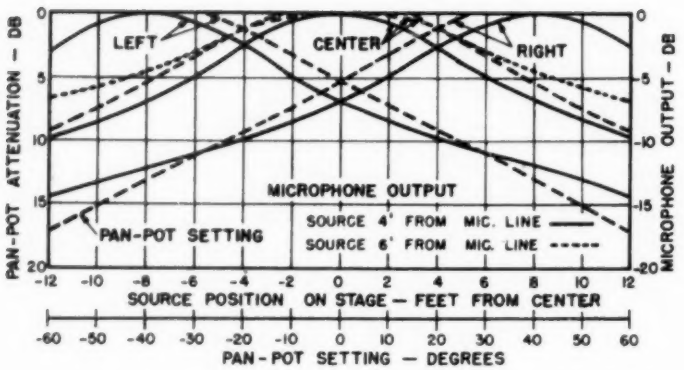


Fig. 5. Pan-pot characteristics. As a source moves across a pickup stage, the direct sound microphone outputs vary as shown. The dashed line is the corresponding attenuation introduced by the pan-pot constructed for a 1934 demonstration.

shown by the dashed lines in Fig. 5. The control was made of three continuous-winding ladder volume controls modified with "bridges" for the sliders over parts of the angular range to give the flat portions of the curves. The solid lines of Fig. 5 show the variation in direct sound at each microphone for a source moving across a line 4 ft from the microphones, which are assumed 8 ft on centers.

It can be seen that this simple volume control scheme is a fair representation of the actual case. The dotted curve shows for comparison the variation in level for the center microphone when the source moves across a line 6 ft from the microphones. The difference between these curves emphasizes that the relationships vary for different stage depths, and in using a pan-pot the operator must adjust his settings to the desired effect. The curves also show the rather small level differences that exist. It will be seen that the pan-pot characteristic gives lower channel levels at "side" settings than the actual pickup. This is desirable to compensate for the absence of arrival-time and microphone directivity effects.

Disk Recording

The adaptability of tape- and film-recording methods to stereophonic sound is readily apparent, and these strip media are relatively unlimited as to number of channels. For two-channel recording, disk methods are also practicable. Two systems have been demonstrated. In one[47] two grooves are used in parallel, one starting near the outer edge and one near the middle of the recording area. Two reproducers are used. In the other[18,48,49] a single groove is used, with one channel recorded as a vertical and the other as a simultaneous lateral track. While the interaction or crosstalk between channels is relatively high, experiment has shown that a sufficient ratio for stereophonic work can be obtained.

CONCLUSION

Although stereophony is attaining a respectable age, much more information must be obtained before it can be said to rest on a foundation of quantitative relationships. It is hoped that this summary of present knowledge will stimulate the acquisition of this information, and in the interim will serve as a useful guide to those who must make recordings without waiting for complete theoretical understanding.

REFERENCES*

1. A. G. Bell, "Experiments relating to binaural audition," *Am. J. Otol.*, July 1880.
2. H. Fletcher, "Hearing, the determining factor for high fidelity transmission," *Proc. I. R. E., 30:* 266, June 1942.

3–10: A series of articles published in the *Philips Technical Review:*

3. K. de Boer and R. Vermeulen, "On improving of defective hearing," *1, no. 1:* 317, Nov. 1939.
4. K. de Boer, "Stereophonic sound reproduction," *5, no. 4:* 107, Apr. 1940.
5. K. de Boer, "Experiments with stereophonic records," *5, no. 6:* 183, June 1940.
6. K. de Boer, "Stereophonic recording on Philips-Miller film," *6, no. 3:* 80, Mar. 1941.
7. K. de Boer and A. TH. van Urk, "Some particulars of directional hearing," *6, no. 12:* 359, Dec. 1941.
8. K. de Boer, "The formation of stereophonic images," *8, no. 2:* 51, Feb. 1946.
9. K. de Boer, "A remarkable phenomenon with stereophonic sound reproduction," *9, no. 1:* 81, 1947.
10. R. Vermeulen, "Duplication of concerts," *10, no. 6:* 169, Dec. 1948.
11. G. W. Stewart, "The function of intensity and phase in binaural location of pure tones," *Phys. Rev.:* 425, May 1920.
12. R. V. L. Hartley and T. C. Fry, "The binaural localization of pure tones," *Phys. Rev., 18:* 431, Dec. 1921.
13. W. G. King and D. A. Laird, "The effect of noise intensity and pattern on locating sounds," *J. Acoust. Soc. Am., 2, no. 1:* 99, July 1930.
14. E. Meyer, "Stereoacoustics," *E.T.Z., 46:* 805, May 28, 1925.
15. K. Holt-Hansen, "Researches on the localization of sound," *Z. Psych., 120:* 209, 1931.
16. J. H. Shaxby and F. H. Gage, "Studies in localization of sound, a, the localization of sounds in the median plane," Special Report Series 166, Medical Research Council, London, circa 1933.
17. H. Wallach, E. B. Newman and M. R. Rosenzweig, "The precedence effect in sound localization," *Am. J. Psych., 62, no. 3:* 315, July 1949.
18. J. Moir and J. A. Leslie, "Stereophonic reproduction of speech and music," *J. Brit. I.R.E., 12, no. 6:* 360, June 1952.
19. F. M. Doolittle, U. S. Patent 1,817,177 (Aug. 1931) and U.S. Patent 2,126,370 (Aug. 1938).
20. E. H. Foley, U.S. Patent 1,589,139 (June 1926).
21. John M. Conly, "Hearing with both ears," *The Atlantic*, 89, Feb. 1953.
22. L. J. Sivian and S. D. White, "Minimum audible sound fields," *J. Acoust. Soc. Am.:* Apr. 1933.
23. J. P. Maxfield, "Some physical factors affecting the illusion in sound motion pictures," *J. Acoust. Soc. Am.:* July 1931.
24. J. G. Frayne and H. Wolfe, *Sound Recording*, John Wiley and Sons, New York, 1949.
25. V. O. Knudsen and C. M. Harris, *Acoustical Designing in Architecture*, John Wiley and Sons, New York, 1950.

26–31: Symposium on Reproduction in Auditory Perspective published in *Elec. Eng., 53:* 9, Jan. 1934; and in *Bell Sys. Tech. J.*, Apr. 1934.

* The list includes those mentioned in the text, plus others considered of interest. The listed publications also contain additional references.

26. Harvey Fletcher, "Basic requirements." (Reprinted in *Jour. SMPTE, 61:* 415–419, Sept. 1953.)
27. J. C. Steinberg and W. B. Snow, "Physical factors." (Reprinted in *Jour. SMPTE, 61:* 420–430, Sept. 1953.)
28. E. C. Wente and A. L. Thuras, "Loudspeakers and microphones." (Reprinted in *Jour. SMPTE, 61:* 431–446, Sept. 1953.)
29. E. O. Scriven, "Amplifiers."
30. H. A. Affel, R. W. Chesnut and R. H. Mills, "Transmission lines."
31. E. H. Bedell and I. Kerney, "System adaptation."
32–38: A Symposium on the Stereophonic Sound Film System, *Jour. SMPE, 37:* 331, Oct. 1941.
32. Harvey Fletcher, "General theory."
33. E. C. Wente, R. Biddulph, L. A. Elmer and A. B. Anderson, "Mechanical and optical equipment."
34. J. C. Steinberg, "Pre- and post-equalization of compandor systems."
35. W. B. Snow and A. R. Soffel, "Electrical equipment."
36. E. C. Wente and R. Biddulph, "A light valve."
37. E. C. Wente and A. H. Müller, "Internally damped rollers."
38. L. A. Elmer, "A non-cinching film rewind machine."
39. L. D. Grignon, "Experiment in stereophonic sound," *Jour. SMPE, 52:* 280, Mar. 1949. (For an augmented version of the same paper, see *Jour. SMPTE, 61:* 364–379, Sept. 1953.)
40. C. A. Lovell, U. S. Patent 2,261,628 (Nov. 1941).
41. W. B. Snow, U. S. Patent 2,137,032 (Nov. 1938).
42. A. J. Forman, "A new multiplex system for three dimensional sound," *Tele Tech, 12, no. 4:* 92, Apr. 1953.
43. "Cinerama," *International Sound Technician, 1, no. 1:* 4, Mar. 1953.
44. A. W. Colledge, *Western Electric Oscillator, 4, no. 11:* 1946.
45. "Paramount Night of Stars," Special Benefit Concert for Philharmonic Orchestra Continuance Fund, *Hollywood Bowl Magazine,* Aug. 17, 1936.
46. W. J. Albersheim and D. MacKenzie, "Analysis of sound film drives," *Jour. SMPE, 37:* 452, Nov. 1941.
47. E. Cook, "Recording binaural sound on discs," *Tele Tech, 11, no. 11:* 48, Nov. 1952.
48. Unpublished work at Bell Telephone Laboratories.
49. W. B. Jones, U.S. Patent 1,855,150 and U.S. Patent 1,855,151 (Apr. 1932).
50. W. L. Douden, U.S. Patent 2,124,030 (July 1938).
51. R. T. Friebus, U.S. Patent 2,114,049 (Apr. 1938) and U.S. Patent 2,249,606 (July 1938).
52. H. Fletcher, U.S. Patent 2,254,034 (Aug. 1941).
53. A. Rosenberg, British Patent 23,620 (1911).
54. Holst and de Boer, U.S. Patent 2,273,866 (Feb. 1942).
55. J. C. Steinberg and W. B. Snow, U.S. Patent 2,126,929 (Aug. 1938).
56. W. B. Snow, U.S. Patent 2,258,662 (Oct. 1941) and U.S. Patent 2,304,856 (Dec. 1942).
57. O. L. Guernsey, Jr., "The 3-dimension fever grips Hollywood," *New York Herald Tribune,* Feb. 15, 1953.
58. Perfect Transmission and Reproduction of Symphonic Music in Auditory Perspective: Forword, F. B. Jewett; Part I, The Demonstration, W. B. Snow; Part II, Transmission, H. S. Hamilton, *Bell Telephone Quarterly, 12, no. 3:* 156, July 1933.
59. E. H. Bedell, R. E. Crane, W. B. Snow and A. L. Thuras, "Technical problems of stereophonic reproduction," *Bell Laboratories Record, 12, no. 7:* 194, Mar. 1934.
60. Analytic Subject Index to Contemporary Acoustic Literature, Sec. 4.3, Binaural Hearing: Localization, *J. Acoust. Soc. Am., Cumulative Index, vols. 11 to 20:* 1948.
61. M. B. Sleeper, "Sound movement and dimensions," *FM-TV, 11, no. 1:* 48, Nov. 1951.
62. Raymond Spottiswoode, "Progress in three-dimensional films at the Festival of Britain," *Jour. SMPTE, 58:* 291, Apr. 1952.
63. Norman Jenkins, "The cash customers at the Festival of Britain Telecinema," *Jour. SMPTE, 58:* 304, Apr. 1952.
64. Otto Bixler, "A commercial binaural

recorder," *Jour. SMPTE, 59:* 109, Aug. 1952.
65. Harvey Fletcher, "Stereophonic recording and reproducing system," *Jour. SMPTE, 61:* 355–363, Sept. 1953.
66. John K. Hilliard, "Loudspeakers and amplifiers for use with stereophonic reproduction in the theater," *Jour. SMPTE, 61:* 380–389, Sept. 1953.
67. J. G. Frayne and E. W. Templin, "Stereophonic recording and reproducing equipment," *Jour. SMPTE, 61:* 395–407, Sept. 1953.
68. J. E. Volkmann, J. F. Byrd and J. D. Phyfe, "New theater sound system for multipurpose use," *Jour. SMPTE, 61:* 408–414, Sept. 1953.

Discussion

John G. Frayne (*Westrex Corp.*): Would the speaker tell us whether there's ever any possibility of duplicating the real stereophonic effect by using the artificial method of taking a monaural track and making it into stereophonic by manipulation of gain and equalization.

Mr. Snow: I don't think so, because by manipulation of the channels you do not duplicate all the effects which you can get on a real stage. As the speaker, let's say, walks across the stage you can get the actual effect of the intensity increase, you automatically get the effect of the arrival time with sound coming earlier from the nearest channel. You can use microphone directivity, if you use it with care, to enhance both of those effects; and it seems to me that, at least without something that I can't quite imagine in elaboration, it would be awfully hard for any one person to duplicate all these effects as he tried to twist some knobs. And, of course, there's another thing: no matter what you try to do in this way, you can do it for only one source at a time, if you're doing it artificially, whereas the actual pickup will handle any number of sources all at one time. My own feeling is that it is very unlikely that the completely artificial manipulation of channels will give you a real duplication of multiple-channel pickup at the original scene.

Dr. Frayne: In that case, would you say then that the industry is missing an opportunity of improved sound presentation by placing so much emphasis on the pan-pot method of producing stereophonic sound?

Mr. Snow: I would say that they ought to consider that something to get rid of as soon possible. It's something which can be used to advantage, I'm sure, in many situations; but I feel that it should be used only as a last resort, rather than as a first resort. It won't sound as good as the real pickup or the original.

Dr. Frayne: On the matter of the number of channels, I notice you say that three channels give a very good stereophonic effect. Now, in Cinerama, I believe, they use five stereophonic channels behind the screen and I am told by Cinerama engineers that they find a much better stereophonic effect by using five rather than three.

Mr. Snow: I use three for two reasons. One is that my personal experience has been with two or three and it makes the fundamentals easier to show. The fundamental principles I don't think would change with the number of channels, but I do feel that the number of channels depends upon the width of the stage, the width of the scene that you're going to cover and perhaps as a rule of thumb, you might say that a channel should not cover more than a width of 20 or 25 ft with a single channel. The cinerama screen is so much bigger than the 50-ft wide total that they needed more channels.

Dr. Frayne: In the case of CinemaScope, which uses in some cases a 65-ft screen, is it possible to cover that with three speakers?

Mr. Snow: I imagine that probably it will be thought so. I don't mean to sound as facetious as that. Actually, when you have a picture, you don't need to have as faithful sound localization as when you're only trying to reproduce an orchestra with nothing to look at, as I have usually done in my work. The picture certainly can complement the "monophonic" sound to some extent, as we're all well aware, since we've been getting along with one channel on any width screen up to now. As a matter of fact, I would think in a picture, up to the width that you spoke of, that would be satisfactory. I have no doubt, however, that more channels would be even more realistic, but it's certainly a matter of economics.

Dr. Frayne: What do you think of the auditorium speakers as adding to stereophonic effect?

Mr. Snow: That's something for the industry to decide now. I haven't had any personal experience with that. I have nothing against it. My feelings on stereophonic effects are that you manipulate the channels to get the effects you want. I was trying to point out the fundamentals that you have to preserve to get those effects, but I feel that when you get to the point of having auditorium speakers, and so on, it gets a little bit more in the showmanship angle than straight physics. And I'll leave that to the showman.

Edward S. Seeley (Altec Service Corp.): Do you believe it possible to recreate a location outside of the outermost speaker in a three-channel system?

Mr. Snow: Not acoustically, but with a picture I do think you can. However, there doesn't seem to be anything in the physics or physiology that I know of that would pull the sound past the outside loudspeaker just from the standpoint of localizing the sound with your eyes shut, but obviously if you have a picture, with a sound source that's outside the outside loudspeaker it's not very hard to imagine that the sound is pulled somewhat outside of the actual physical source of it. But you can see, from the standpoint of sound alone, that if you turned off all the channels but the one on the side that we're talking about, everybody would localize the sound right in that loudspeaker and there's nothing I can see that would make you pull it any further than that when the other ones are running.

Loren L. Ryder (Paramount Pictures Corp.): With respect to the remarks I am about to make, I will first say that my comments are not against stereophonic sound. Now with respect to what can be done by panning sound, we at Paramount have found that following some of the principles that were explained here but using phase displacement, rather than volume, we can more definitely control the placement of sound than by the volume difference between loudspeakers. We also find that equalization, as mentioned by the speaker, is a very strong control. We at Paramount have used displacement (phase shift) by as much as four and as high as seven sprocket holes in the control of sound placement. Having once established that type of sound placement, it makes little difference what volume is used from the three loudspeakers as far as the listener is concerned, and as far as his selection of a point source. Therefore, with such an arrangement, we can gain a proper directivity much further to the side of the theater and further down toward a side loudspeaker, than we have ever been able to obtain either by volume control or by classical stereophonic sound.

Mr. Snow: I'm very glad to hear of some practical experience along that line, because I certainly would expect that on the basis of the principles I was enunciating here; but unfortunately I have never been able to try it. Thanks very much for that comment.

Mr. Seeley: May I ask Mr. Ryder if his remarks apply to simultaneous sounds from distributed sources as well as to dialogue?

Mr. Ryder: My remarks apply to dialogue, music and sound effects. In the picture *Shane* there are sequences in which the violin section of the music is on the left-hand loudspeaker, the music base is on the right, dialogue is center screen, calls are heard from the left side of the screen and sound effects are moving back and forth.

We find no trouble in gaining proper placement of sound effects and we find no confusion when these sounds are ultimately reproduced in the theater. It seems to me that there is a great deal still to be learned in regard to the effective handling of sound when reproduced from three or more loudspeaker systems. For those who have not experimented with phase shifting, I recommend that they do so.

It is our feeling that there are a number of ways of gaining the same effectiveness to the audience. The real question is — which way is the simplest, least costly, and least subject to error and disturbing effects.

Richard H. Ranger (Rangertone, Inc.): I think that we all owe a debt of gratitude to Dr. Snow for this elucidation of these principles and I'd like to check again on what Mr. Ryder has just said, that timing has a terrific effect on directivity. We are indebted to Dr. Haas of Göttingen for work on this timing business, because he has elucidated this matter very intensively and confirms what has just been said. In other words, timing is of the utmost importance and you can actually get a curve or a correspondence, shall I say, between timing and intensity. In other words, as Mr. Ryder has just suggested here, you can move a subject across the stage just by

timing; and you can also move it just by intensity. And you can do the corresponding thing of making them compensate each other. In other words, you can move the timing so as to make the apparent location move to the left, we'll say, and you can increase the intensity to hold it where it was. And you soon find, however, that when you do that the timing completely outweighs the intensity, so that actually the timing becomes in many ways the controlling factor. As to flutter and other quality factors, it has been my finding that they are entirely determined by the sound that you get first, or should I say that they are greatly determined by that. You can have considerable flutter, if you please, in the sound that comes later, and it will not affect the apparent quality at all. Timing and intensity, then, are terrifically important in these things. I don't quite go along with the statement that timing is the only essential, however. Perhaps Mr. Ryder did not intend to give that impression.

Mr. Ryder: It is certainly possible to control placement with intensity.

Col. Ranger: In fact, I feel that you can overdo the timing business, because you get a little bit of an uncertainty, if I might put it that way, when you get too much intensity from the wrong speaker, which you can do. You get a confusion of sound, so I feel that the answer is going to be a judicious use of the two to come up with the best quality.

Mr. Ryder: A further comment along the line of Col. Ranger's thoughts: if you use timing and equalization and volume, you have a very smooth complete control, and it's not as awkward to do as one would think. In this regard, we can refer to the picture *Shane*, which is largely handled by timing and not by volume. I should also comment that in all the work with respect to motion pictures where it is necessary to do much editing and cutting of motion pictures so that there is a change in sound placement on cuts, I personally favor a minimum movement of dialogue and a maximum use of stereophonic for punctuation in storytelling for effects and for music.

Walter Brecher (Leo Brecher Theatres): In connection with the finding that the number of channels to use with a wide screen should be based on a spacing of about 20 ft by channel, there are a great many theaters whose total width is in the neighborhood of 30 to 40 ft. It's my impression that there is a radius of illusion of approximately 15 ft which is centered on each speaker and in view of the acknowledgment that the visual pull does affect the illusion of location of sound source, does stereoscopic sound offer any substantial benefit for a theater of the dimensions that I have described?

Mr. Snow: I didn't mean to imply that. Let's put it another way. I meant that I felt that until people have actual data on it, that that was a fairly good rule of thumb as to the width where you might begin to consider that you might need more channels. But the stereophonic system will improve the reproduction in a living room where the loudspeakers are 5 ft apart or 12 ft apart, so that what I gave is in my opinion, a maximum width, and for anything smaller than that you can definitely get an improvement by using multiple channels. You might say, well, why not just use two channels? I believe that that would just make it more difficult from the pickup standpoint to get the effects you want, particularly when so much of the sound should come from the center of the stage for close-ups. When you have a third channel you can pretty nearly guarantee that for most of the seats in the auditorium. You're trying to build the illusion. With loudspeakers just at the sides, that's much harder to do.

Psychometric Evaluation of the Sharpness of Photographic Reproductions

By ROBERT N. WOLFE and FRED C. EISEN

Psychometric methods were used to evaluate the relative sharpness of a number of photographic reproductions in which sharpness was the only significant variable. Since sharpness is an observer's subjective impression of an aspect of picture definition, the methods for deriving sharpness values involve introspective processes and methods of quantifying these subjective impressions. Although no physical measurements of any aspect of the stimulus are involved in deriving sharpness values by the psychometric method, repeated evaluations showed that the scale values obtained are a reliable indication of the sharpness attribute of a photographic reproduction. Three methods of quantifying the judgment data were used, and the sharpness ratings obtained from all three were in good agreement with one another. Projected transparencies gave substantially the same results as paper enlargements. Attempts to correlate the sharpness ratings with physical measurements of some aspect of the developed image were not entirely successful; neither resolving power nor simple density relationships across an abrupt boundary between light and dark areas resulted in satisfactory correlations with sharpness ratings.

THE SHARPNESS of a photographic reproduction is a subjective concept associated with one of the impressions made on the mind of an observer when viewing a picture. Specifically, it is the impression produced by that aspect of picture definition which is affected by lens quality, lens focus, by the type of photographic material used, and by other factors in the photographic process. Since sharpness is a subjective concept, it cannot be evaluated directly by means of physical measurements, although a physical correlate may be found to exist. It is therefore necessary to employ psychometric methods to derive sharpness values. Psychophysical methods may be utilized subsequently to establish a correlation between sharpness and purely objective measurements of some aspect of the photographic image. Such an approach has been used by Baldwin[1] and by Mertz, Fowler and Christopher[2] in studies of television images.

Communication No. 1527 from the Kodak Research Laboratories, by Robert N. Wolfe and Fred C. Eisen, Kodak Research Laboratories, Eastman Kodak Co., Rochester 4, N.Y. Reprinted from *Journal of the Optical Society of America, 43:* 914–922, Oct. 1953.

The present paper deals primarily with the psychometric evaluation of sharpness, and refers only briefly to a preliminary search for a physical correlate. The subject may be conveniently treated in three parts: (1) technique and precision of psychometric methods applicable to sharpness evaluations, (2) the effect of picture-making technique and test-picture subject matter on sharpness, and (3) results of a preliminary search for a physical or objective correlate.

Psychometric Methods

Since psychometric methods involve only introspective processes and methods of quantifying these subjective impressions, the reliability of the results obtained must be determined by repeating observations and by comparing different methods of quantification. To investigate the reliability of the psychometric methods involved in obtaining picture-sharpness ratings, a series of photographs which varied in sharpness were made. The test picture was the "patio" scene shown in Fig. 1. The negatives for these pictures were made by using ten different negative films, arbitrarily identified by numbers 1 to 10, each film being developed to give the same average density-log exposure (D-log E) gradient. These negatives varied in sharpness as the negative materials varied with respect to those qualities which influence the sharpness of recorded images. The negatives could themselves have been submitted to a group of observers for appraisal, but there were reasons for not doing so. In the first place, since most observers are not accustomed to viewing negatives, a more normal reaction can be expected from an examination of conventional positives; it is conceivable that sharpness impressions would be different when viewing a negative than when viewing a positive. Furthermore, the negatives, although matched in D-log E gradient over the exposure range of the picture, were not all of the same density level. These differences in density were compensated for in making the positives, in order to obtain prints that matched one another in tone reproduction. It was decided, therefore, that positive prints from each of the negatives should be used for the sharpness appraisals.

Positives of the ten negatives were made by (a) enlarging approximately four times onto photographic paper and (b) contact-printing onto lantern-slide plates. The contact-printing operation was carried out with a vacuum printing frame so that good transfer of the structural detail of the negative to the positive material was assured. The enlargements were made in a conventional enlarger, which was carefully focused for each negative. Two sets of enlargements were made to determine how accurately the print-making process could be repeated.

Sharpness Judging and Quantification of Data. In presenting the pictures to the observers, only very general instructions were given. No prompting or tutoring which might influence their reactions was permitted. The observers were all experienced in judging the quality of photographic reproductions but they were not aware of the devices that had been employed in altering the appearance of the pictures they examined. Each observer was requested to study the pictures and thereafter to express his opinion of their relative "sharpness." The specific term "sharpness" was always used, so the particular aspect of the reproduction that was appraised was the one which the word "sharpness" evoked in each observer's consciousness. Although no attempt was made to define the term, none of the observers appeared to be uncertain of its implications, and with very little hesitancy they all proceeded to make unqualified decisions.

Since there is no established unit of picture sharpness, all the results are

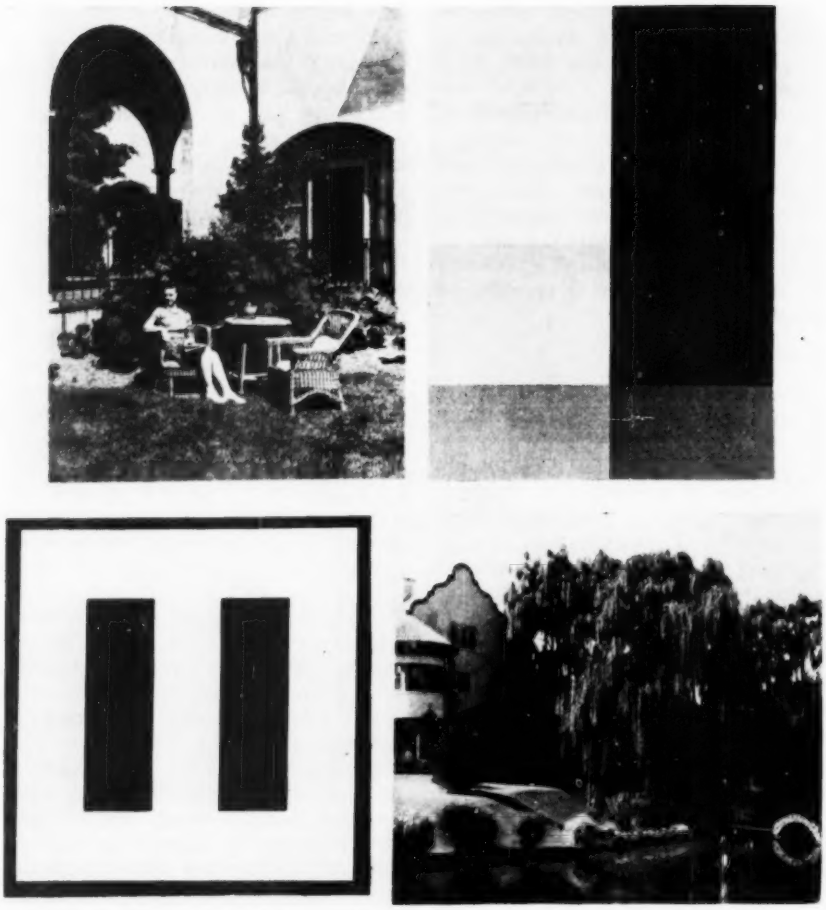


Fig. 1. Test objects used to investigate psychometric methods and effect of subject matter on sharpness judgments. "Patio" (above—left); "density patch" (above—right); "square" (below—left); "willow pond" (below—right).

relative. It follows, therefore, that sharpness evaluations can only be made by comparing one picture with another or with several others. Although an observer may have a definite impression that one picture is sharper than another, he normally does not appraise the difference numerically. The conversion of subjective impressions into numerical scale values is required for convenient utilization of the judgment data. This quantification of subjective impressions can be achieved by various methods, of which the following were considered in this work: (1) quantification by the observer himself, in which the observer is requested to express his impressions of sharpness in the form of numerical ratings; (2) quantification by statistical means after a number of observers have

Table I. Sample Data of Sharpness Ratings for First Set of Prints Obtained by Method of Observer Quantification.

Observer:	1		2		3		4		...20	
Negative material	As given	Adjusted	As given	Adjusted	As given	Adjusted	As given	Adjusted	Avg of 20 adjusted ratings	Prorated avg adjusted ratings
1	70	60	60	60	30	60	73	66	60.3	62
2	88	84	80	80	50	71.5	84	80	75.8	78.5
3	80	73	72	72	45	68.5	68	60	72.5	75
4	85	80	83	83	55	74	77	71	74.8	77
5	100	100	100	100	100	100	98	97.5	99.4	102.5
6	90	87	69	69	50	71.5	80	75	77.6	80
7	92	89	92	92	85	91.5	90	87.5	90.9	94
8	98	97.5	100	100	100	100	100	100	96.8	100
9	94	92	92	92	65	80	93	91	89.1	92
10	99	98.5	95	95	68	82	94	92.5	92.2	95

Equation for adjusting ratings to specified minimum value:

$$R' = 100 - \frac{(100 - R_s)(100 - R)}{100 - R_m}.$$

R = rating to be adjusted.
R' = adjusted rating.
R_m = minimum value as given by observer.
R_s = minimum value of adjusted ratings.

arranged the pictures in the order of their sharpness; and (3) quantification by the experimenter, who asks the observer to classify his impressions as "slightly sharper" "much less sharp," etc., and then arbitrarily assigns numerical values to each category. Regardless of which method is used, the numerical value of sharpness is nevertheless arbitrary and has no physical significance *per se*. The importance of the value is in the relationship it bears to other picture-sharpness ratings.

The first point to be determined was the reproducibility of the results, which could be taken as an index of the precision of the respective methods of evaluation. The first or observer-quantification method was studied by submitting the two sets of enlargements from the ten negatives, one set at a time, to twenty observers, who were asked to arrange the pictures in the order of their sharpness and to assign to each picture a numerical rating indicating the observer's opinion of its relative sharpness. The picture which an observer considered sharpest was always assigned a rating of 100, and each observer was free to assign the ratings for the remaining pictures according to his impressions of their sharpness. However, each observer's ratings for each set of prints were later adjusted so that the least sharp picture had a rating of 60 for that particular observer. The same ratio of rating differences was maintained in making this adjustment, while the sharpness values were brought to a common scale. The adjusted ratings of the twenty observers were then averaged, and the averages were prorated to make the rating for picture No. 8 equal to 100. Sample data to illustrate this procedure, as used for the first set of prints, are shown in Table I. A graphical comparison of the ratings obtained from the two sets of prints is shown by graph A in Fig. 2.

The second or statistical method of quantification was then applied to the data obtained from the judging of the enlarged prints. In this method, the

Table II. Derivation of Sharpness Ratings From Order Numbers.

Negative material	1	2	3	4	5	6	7	8	9	10
Observer					**Order numbers**					
1	10	7	9	8	1	6	5	3	4	2
2	10	7	8	6	1.5	9	4.5	1.5	4.5	3
3	10	7.5	9	6	1.5	7.5	3	1.5	5	4
4	9	6	10	8	2	7	5	1	4	3
•										
•										
•										
20										
$P = \frac{\Sigma r_1 - 0.5N}{nN}$	0.943	0.672	0.748	0.725	0.078	0.668	0.316	0.145	0.379	0.286
t	1.58	0.45	0.67	0.60	−1.42	0.43	−0.48	−1.06	−0.31	−0.57
$-(t - 1.58)$	0	1.13	0.91	0.98	3.00	1.15	2.06	2.64	1.89	2.15
Prorated $100 \sim 2.64$	0	43	34.5	37	113.5	43.5	78	100	72	81.5
Adjusted $62 \sim 0$	62	78	75	76	105	78.5	91.5	100	89	93

P = proportion of the area under the normal distribution curve.
r_1 = order number.
N = number of observers.
n = number of pictures.
t = ordinate of normal distribution curve determined by the proportion of the area under the curve.

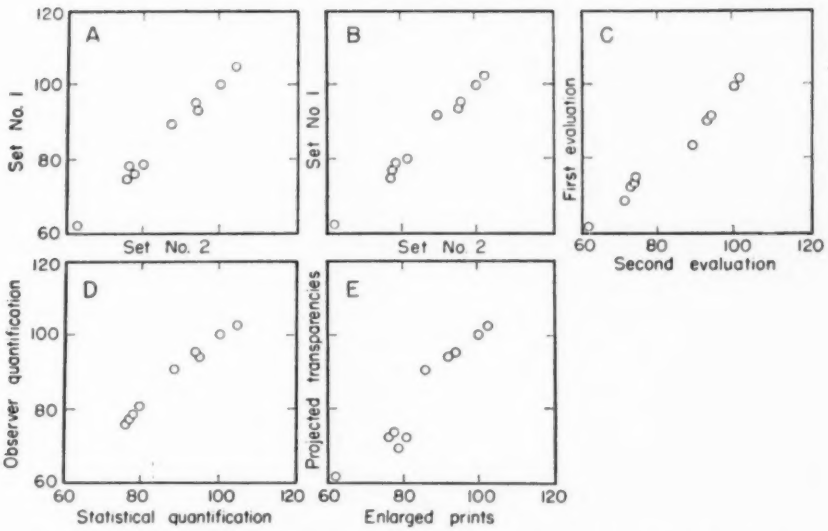


Fig. 2. Comparison of relative picture-sharpness ratings made under various conditions: A, two sets of enlargements from same negatives, observer quantification; B, enlargements from same negatives, statistical quantification; C, two observations at different times, same projected transparencies, paired comparison; D, same enlargements, observer quantification as ordinates, statistical quantification as abscissas; E, same negatives, projected transparencies by paired comparison as ordinates, enlargements by observer quantification as abscissas.

numerical ratings assigned by the observers were not needed, since only the ranking data were used. To derive sharpness ratings from the order numbers, Guilford's method based on a composite standard[3] was used. The scale values obtained by this method depend upon the number of times each picture was ranked in each position in the 1 to 10 range. When an observer selected two or more pictures equal in sharpness, each of the equally ranked pictures was given an order number which was the average of as many successive order numbers as there were equally ranked pictures. For instance, if, after three pictures had been arranged in a descending order of sharpness, the next two pictures were considered equal in sharpness, the order number that would be assigned to each of these two pictures would be 4.5, the average of rank positions 4 and 5. The procedure used to derive sharpness ratings from the order numbers is illustrated in Table II. The final ratings were adjusted to be 62 and 100 for pictures Nos. 1 and 8, respectively, of both sets, which were the values obtained in the preceding method of quantification. The ratings obtained for the two sets of enlargements are plotted against each other as graph B of Fig. 2.

The third method of quantification was employed in obtaining numerical ratings of sharpness for the positive transparencies made from the same ten negatives. In this case, the psychometric data were derived from sharpness appraisals made by a "paired-comparison" procedure. The observers were requested to view two pictures

Table III. Sample of Paired-Comparison Data. Slide No. 7 Compared With Each of the Others.

Film		1	2	3	4	5	6	7	8	9	10
Observer	A	−0.3	−0.2	−0.1	−0.2	+0.1	0.00		−0.1	0.00	0.00
	B	−0.3	−0.1	−0.1	−0.1	+0.2	−0.2		+0.1	0.00	+0.2
	C	−0.3	−0.1	−0.2	−0.1	+0.2	−0.1		+0.1	0.00	+0.1
	D	−0.2	−0.1	−0.1	−0.1	+0.2	−0.2		+0.1	0.00	0.00
	E	−0.2	0.00	+0.1	−0.1	+0.2	−0.1		+0.1	−0.1	+0.2
	F	−0.2	−0.2	0.00	−0.1	+0.2	0.00		0.00	+0.1	+0.1
	G	−0.2	−0.2	−0.1	−0.1	+0.1	0.00		0.00	0.00	0.00
	H	0.00	−0.1	+0.1	0.00	+0.1	+0.1		+0.1	+0.2	+0.2
	I	−0.2	−0.1	−0.1	0.00	+0.2	0.00	Comparison	+0.2	+0.1	+0.1
	J	−0.2	−0.1	−0.2	−0.2	+0.2	−0.1	Slide	+0.2	+0.2	+0.2
Avg.		−0.21	−0.12	−0.07	−0.10	+0.17	−0.06	0.00	+0.08	+0.05	+0.11
Rel. Log Sharpness		1.79	1.88	1.93	1.90	2.17	1.94	2.00	2.08	2.05	2.11
Rel. Sharpness		62	76	85	79	148	87	100	120	112	129
Prorated		52	63	71	66	123	72	83	100	93	107

projected simultaneously on a screen by two slide projectors. A group of ten observers viewed the pictures and made individual judgments. Two assistants located very close to the screen operated remote-control focusing devices for maintaining the best possible focus during judging. Each of the ten positives was compared with every other positive twice, once in each projector, in order to eliminate any difference in the quality of the projectors. Thus, a total of ninety comparisons was made. The observers were asked to give their impressions of the comparative sharpness of the two adjacent pictures in terms of the following seven ratings:

1. Picture A much sharper than Picture B;
2. Picture A sharper than Picture B;
3. Picture A slightly sharper than Picture B;
4. Picture A equal in sharpness to Picture B;
5. Picture A slightly less sharp than Picture B;
6. Picture A less sharp than Picture B; or
7. Picture A much less sharp than Picture B.

Numerical values of 0.3, 0.2, 0.1, 0.0, −0.1, −0.2 and −0.3, respectively, were arbitrarily assigned to each of these qualitative ratings. These numbers were treated as increments in a scale of logarithmic sharpness ratings. The final scale values were antilogarithms of the scale values derived from these numerical increments.

After ninety comparisons were made, numerical sharpness values were assigned, on the basis of the observers' ratings, to each comparison for each observer. For example, if an observer indicated that he considered Picture A to be slightly sharper than B, then for that comparison, Picture A was assigned a value of 0.00 and Picture B was assigned a value of −0.10. The values determined by the ten observers for each comparison were averaged and used as

a basis for calculating ninety relative sharpness ratings which were prorated to make the rating for picture No. 8 equal to 100. Table III illustrates this part of the procedure, using data obtained from comparisons No. 73 to 81, for which picture No. 7 was used in all cases as one member of the pair. From the ninety comparisons made, each of the other nine pictures had ten separate sharpness ratings relative to that of the positive from negative No. 8, either by direct or indirect comparison. These ten relative sharpness ratings were averaged and the resulting values were taken as the picture-sharpness ratings of the positives relative to the positive from negative No. 8.

The same positive transparencies were rated again a few weeks after the first evaluation, using the same procedure and the same observers. The two sets of ratings were adjusted to make picture No. 1 rate 62 as before, No. 8 remaining at 100, and the two sets are compared as graph C of Fig. 2. A good correlation is indicated.

It is of interest to compare the results obtained by the various methods of evaluating the positives. As pointed out previously, graphs A and B of Fig. 2 show that the two sets of enlargements gave results that are in good agreement with each other for both the observer-quantification and the statistical-quantification methods. Graph C shows that the two sets of transparencies compared by pairs gave results that are in agreement with each other for the experimenter-quantification method. The mean values of the ratings obtained for the two sets by the first and the second methods are compared by graph D, which shows that the two methods are in good agreement. The results obtained from the third method as compared with those obtained from the first two involve differences in the methods of printing the positives and the materials used for them in addition. These results will be discussed below.

Effect of Picture-Making Technique and Test-Picture Subject Matter on Sharpness

Since the paper prints judged for sharpness as described in the preceding section were made by optical enlargement of the negative while the positive transparencies were made by contact-printing the same negatives, a comparison of the ratings obtained from the two types of positives will give some information as to the effect of picture-making technique on sharpness, even though different psychometric methods were used to obtain the ratings. The averages of the sharpness ratings obtained for the transparencies on the two separate occasions were computed, as were the averages of the ratings obtained by the observer-quantification method for the two sets of enlargements. These averages are plotted against each other as graph E in Fig. 2. The departures from a straight line are noticeably greater in this case than in the others, as would be expected considering that another variable has been introduced, but the correlation is still fair. This indicates that the ratings obtained by judging the sharpness of the pictures either as projected transparencies or as paper prints, following any of the procedures described in this report, give a reliable indication of the relative sharpness obtainable with these negative emulsions developed and printed according to the procedures adopted in this work.

Since all the preceding evaluations were made on appraisals of pictures having the same subject matter, it was of interest to determine whether sharpness ratings are dependent upon the composition of the test object used. Therefore, a test was designed for the purpose of determining how much effect, if any, the test-picture subject matter might have on the sharpness evaluation of the pictures.

Six negative-type films, which were expected to produce pictures of different sharpness, were exposed to each of the

Table IV. Sharpness Ratings for Four Test Objects.

Negative material	Ranks converted to relative scale values (ratings)			
	Density patch	Willow pond	Divided square	Patio scene
11	100.0	100.0	100.0	100.0
5	95.2	90.6	93.3	93.7
12	93.3	89.9	88.2	90.0
13	89.3	89.4	85.2	87.2
3	82.5	85.3	82.4	84.8
1	80.0	80.0	80.0	80.0

four test objects shown in Fig. 1. Two of the test objects were the continuous-tone pictures entitled "patio" and "willow pond," while the other two were geometrical patterns with well-defined boundaries, one called the "density-patch" test object and the other the "divided-square" test object. The two picture test objects and the density-patch test object had density scales of approximately 1.30, whereas the divided-square test object was composed of a clear area on a background of density greater than 3.0.

Six negative materials were exposed in contact with positive transparencies of the four test objects and were developed to give the same average *D*-log *E* gradient over an exposure range of approximately 1.30. The divided square was exposed to give a maximum density of approximately 1.50, which was as high as, or higher than, the maximum densities obtained in the other test-object reproductions. The negatives were enlarged five times on suitable enlarging paper to produce positives matched in tone reproduction.

The four sets of six prints were each submitted, one set at a time, to ten observers who were asked to arrange the prints in the order of their sharpness. The sharpness ratings derived from the order numbers of the ten observers by Guilford's method based on a composite standard[3] are shown in Table IV. These ratings, or scale values, have been adjusted to make the rating of the sharpest print equal to 100 and the rating of the least sharp print equal to 80 for each test object. This adjustment is permissible because the terminal points and the scale unit of sharpness ratings derived in this way can be arbitrarily assigned.

Examination of Table IV shows that the negative materials are placed in the same order by the sharpness ratings for each test object, but that the magnitudes of the ratings for a particular negative film vary among the different test objects. This means that the changing of test objects does affect the sharpness ratings but that the effect is small compared with the variation in sharpness ratings caused by differences in the negative materials used in this test. It should be emphasized that even the differences in sharpness among the prints from the different negative materials is small. A statistical examination of the psychometric data indicates that a difference in sharpness represented by about five units of the scale values in Table IV is just significantly noticeable (i.e., a print rated at 100 will be considered sharper than a print rated at 95 in about two-thirds of the judgments). Thus, a difference in sharpness rating caused by a difference in test-object composition can be considered to be quite small and capable of affecting the relative rating of a pair of prints only when the difference in sharpness between prints is so small that it is just noticeable; the most significant variable is the negative material. A summary of the treatment of the data by the analysis of variance leading to these conclusions is given in the Appendix.

The conclusions are based on the appraisal of prints made from normally exposed negatives and do not necessarily apply for overexposed negatives. It is conceivable that when high densities and halation effects are involved, there

might be some types of test objects that would give sharpness values radically different from others.

Search for a Physical or Objective Correlate of Sharpness

With the reliability of the subjectively evaluated sharpness values established, a search for a physical correlate was undertaken. For this phase of the investigation, pictures of the "willow pond" were obtained in which the sharpness was varied by (a) making negatives on a single type of film and varying the position of the film with respect to the focus of the lens in the camera, and (b) using ten different types of film in preparing the negatives from which positives matched with respect to tone reproduction were made, the camera focus being kept constant.

For the first set of pictures, exposures were made to (a) the "willow pond" test object, (b) a high-contrast, three-line resolving-power test object, (c) a similar test object of low contrast, and (d) a single-edge test object. The luminance ratio between characters and background of the high-contrast resolving-power test object was over 1000, while for the low-contrast one it was 1.6. Each of the four test objects was exposed at the same twelve focal positions of the lens. The test objects were restricted to a small field angle to avoid complications arising from field aberrations. Exposure and processing conditions were chosen to give pictures of good tone reproduction, and these same conditions were used for the resolving-power exposures and for the single-edge exposures. Positives of the picture negatives were made in the form of paper prints, and they were evaluated for sharpness by the observer-quantification method described above. The resolving-power values were determined by a visual examination of the negatives, using a suitable viewing magnification, and the density-distance curves were obtained from microdensitometer traces across edges in the negatives.

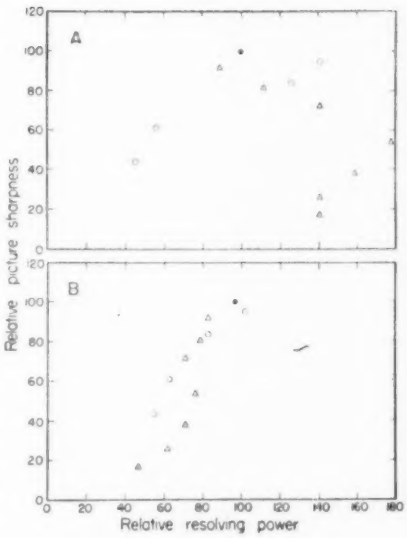


Fig. 3. Comparison of relative picture sharpness with relative resolving power for lens-focus series: A, high-contrast resolving-power test object (luminance ratio over 1000); B, low-contrast test object (luminance ratio, 1.6). ○ Inside focus; ● at focus (point of maximum sharpness); △ outside focus.

The same "willow pond" and single-edge test objects were used for the series in which the negative material was varied. The resolving-power exposures, however, were made in a camera especially designed for the purpose, as described later. The picture negatives were printed on a positive film and evaluated for sharpness by the paired-comparison method already described.

Resolving Power Compared With Sharpness. Although the measurement of resolving power cannot be classified as a purely objective procedure since it involves the visual examination of the images, such measurements are included in this investigation because it is sometimes as-

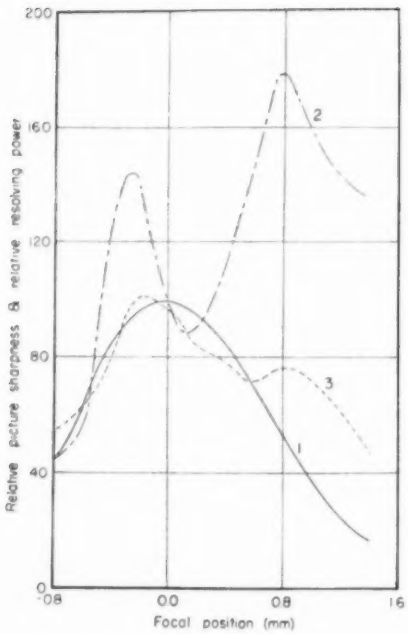


Fig. 4. Relative resolving power and picture sharpness as a function of focal position: 1, sharpness; 2, resolving power, high-contrast test object; 3, resolving power, low-contrast test object. Origin of abscissas at point of maximum sharpness.

sumed that resolving power is the significant measure of the performance of a reproducing system with respect to image definition.

For the lens-focus series, relative picture sharpness is plotted as a function of resolving power in Fig. 3, graphs A and B being for the high- and the low-contrast test objects, respectively. These same data are plotted as functions of the position of the film along the lens axis by curves 2 and 3 in Fig. 4. Curve 1 represents relative sharpness, and the abscissas represent the distance in millimeters from the position of maximum sharpness. It is striking that the position of maximum resolving power for the high-contrast test object is approximately one millimeter from the position of maximum sharpness. The maximum for the low-contrast test object is closer but still is not coincident.

To determine why the position of maximum resolving power does not coincide with the position of maximum sharpness, a point source was photographed under the same conditions as were employed in making the picture negatives. Reproductions of these photographs are shown in Fig. 5. These photographs are the same ones that were published by Herzberger[4] a few years ago except that the focal positions

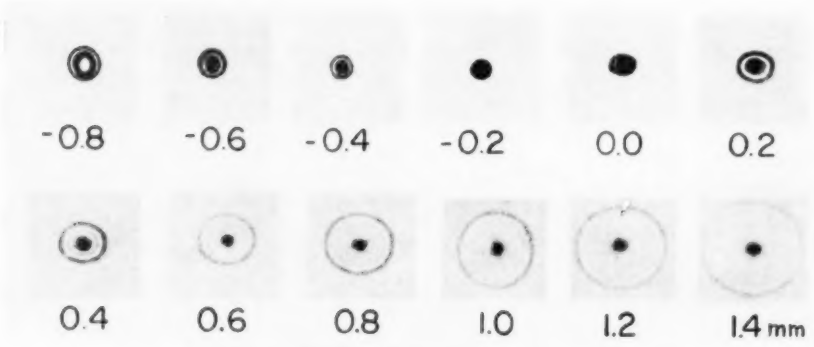


Fig. 5. Images of point source at different focal positions. Positions correspond to abscissas of Fig. 4.

have been labeled anew to correspond with the abscissas of Fig. 4. At the −0.8-mm focus position, which gives low resolving power and poor sharpness, the image consists of circular rings with no central core. These rings form into a fairly compact core at the 0.0-mm focus position, where sharpness is at a maximum and near where one of the resolving-power maxima occurs. The second resolving-power maximum occurs at a focal position of 0.8, where the point-source image consists of a small, sharp nucleus surrounded by an extensive circular blur or haze. This distribution of energy results in the formation of an image of the resolving-power test object in which the lines can be seen distinctly although they are surrounded by an extensive halo. This halo does not interfere with the distinguishability of parallel lines in the images of the resolving-power test object, but it does degrade the edge characteristics of other image elements to such an extent that pictures made at this focal position are distinctly inferior to those made at the position giving maximum sharpness.

The resolving power of the ten films used to make the sharpness series was based on exposures made in a resolving-power camera[5] with a high-contrast, three-line test pattern. Each film was developed as it was for the picture exposures. The maximum resolving-power values obtained from an exposure series are plotted in Fig. 6 as a function of the sharpness ratings; graph A is for a high-contrast test object while B is for a low. Both sharpness and resolving power are expressed in relative terms. It is evident that the correlations are not good enough to establish a psychophysical relationship. The following factors may be responsible for the lack of a better correlation:

(1) The resolving-power values represent measurements made on images in the negatives while the sharpness evaluations were obtained from the positives.

(2) Resolving power is a measure of the least distance between adjacent detail elements which can just be discerned as separate. This limiting distance is related to, but is not a measure of, the sharpness of the detail elements as their proximity to one another decreases.

(3) The resolving-power test images were not similar to the picture negatives in density scale.

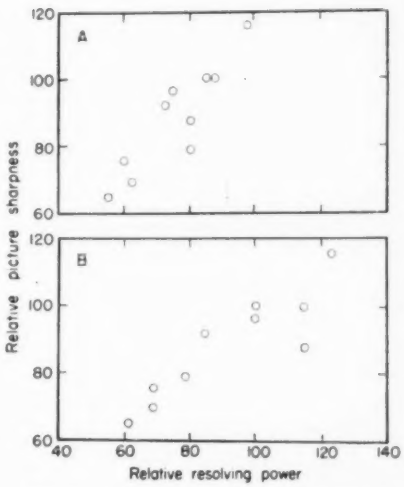


Fig. 6. Comparison of resolving power with picture sharpness, negative-film series: A, high contrast; B, low contrast.

Gradients Compared With Sharpness. Since an observer viewing a photograph gets his impression of sharpness largely from the way that the edges of objects are reproduced, the variation of density across the exposure of an edge is an obvious physical measurement that should be investigated. It seems likely that some aspect of such a density-distance curve derived from photographic images of a knife-edge test object would produce values which would correlate with the sharpness values obtained subjectively. This idea is not new; Ross[6] and others before him have discussed certain features of the density-distance

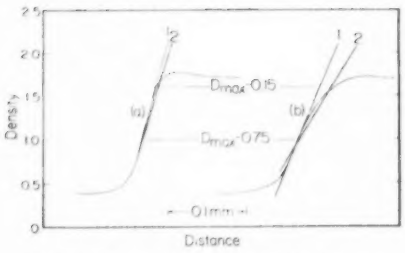


Fig. 7. Examples of density-distance curves obtained at position for (a) sharp picture (0.0 mm) and (b) relatively unsharp picture (−0.6 mm). Straight lines represent (1) maximum gradient and (2) 0.15,0.75 average gradient.

curve in their relation to sharpness, which he defined as "primarily a sensation."* But, although he admitted that such features as the maximum gradient cannot be taken as a measure of sharpness without experimental proof, he offered no subjective data.

For this work, microdensitometer measurements were made across the boundary between the high-density area and the low-density area resulting from exposures to the single-edge test objects. The curves obtained in the lens-focus series at a focal position producing a sharp picture and at a focal position producing a relatively unsharp picture are shown in Fig. 7. Several aspects of the curves obtained at each focal position were measured in an attempt to find a set of values which would correlate well with the sharpness ratings. Figure 7 shows two of the gradients that were measured, (1) the maximum gradient, and (2) an average gradient between a point 0.15 density units less than maximum density and a point 0.75 density units less than maximum density. These gradient values can be compared with the picture-sharpness values in Tables V and VI. Column 3 of Table V relates to the maximum gradient for the lens-focus series while the last column relates to the 0.15,0.75 average gradient. Columns 3 and 4 of Table VI relate respectively to the same quantities for the negative-film series. The last column relates to the values of maximum gradient across the same boundary in the positives. The values in each table have been adjusted so that they are equal for the sharpest and the least-sharp picture condition.

An examination of the data for the lens-focus series in Table V shows that the maximum-gradient criterion does not produce values in the same order as the picture-sharpness values, while the 0.15,0.75 – average - gradient criterion does produce values in almost the same order as the sharpness ratings. However, for the negative-film series data shown in Table VI, none of the gradient measurements produces values in the the same order as the picture-sharpness values. Although the 0.15,0.75-average gradient criterion appears to correlate fairly well with sharpness in the lens-focus series, where the sharpness differ-

Table V. Picture Sharpness and Gradient Values for Lens-focus Series.

Focal position (mm)	Relative picture sharpness	Relative maximum gradient	Relative 0.15,0.75 avg gradient
−0.8	44	62	26
−0.6	61	45	44
−0.4	84	53	69
−0.2	95	69	98
0.0	100	100	100
0.2	92	75	83
0.4	81	44	68
0.6	72	49	51
0.8	54	48	40
1.0	38	31	28
1.2	26	25	23
1.4	17	17	17

* Despite his definition, he followed the contemporary practice of applying the term "sharpness" to the density-distance curve itself.

Table VI. Picture Sharpness and Gradient Values for Negative-Film Series.

Negative material	Relative picture sharpness	Relative maximum gradient (negative)	Relative -0.15,0.75- avg gradient (negative)	Relative maximum gradient (positive)
1	60	60	60	60
2	65	56.5	56	64.5
3	69.5	54	69	53
4	72	65	64.5	76
5	79	94	86	89
6	82	99	88	94
7	85	97	94.5	94.5
8	88	106.5	105.5	94.5
9	88	102.5	112	96.5
10	100	100	100	100

ences are relatively large, it does not seem to correlate so well in the negative-film series, where the sharpness differences are much smaller. This may mean that this particular average-gradient criterion is not satisfactory for detecting small sharpness differences, or it may mean that the sharpness changes caused by film variations are of a different nature from the sharpness changes caused by variations in focusing. From Fig. 7 it is obvious that the maximum gradient bears no relation to the shape of the curve, and this shape could be altered considerably without affecting the value of the 0.15,0.75–average gradient. Thus, changes in the toe and shoulder might not affect the values of this average gradient appreciably, but it is quite likely that they would greatly affect an observer's estimate of sharpness. Since this work was done, the sharpness values obtained from it have been used by Higgins and Jones[7] to develop a criterion that has been described elsewhere. The values given in the present paper are the unpublished data to which these writers refer.

Conclusions

The results of this investigation indicate that sharpness is a definite aspect of picture quality which can be reliably evaluated by psychometric methods. Either projected transparencies or paper prints can be evaluated for sharpness by the methods described in this paper. The relative sharpness values thus obtained do not appear to be dependent to any great extent on the method used to quantify the subjective impressions, nor does the composition of the test object have much effect on the sharpness ratings. Although the preliminary attempts described herein to correlate sharpness ratings with physical measurements of some aspect of the developed image were not completely successful, the ratings themselves have been found useful in other studies of the subject.

References

1. M. W. Baldwin, Jr., "The subjective sharpness of simulated television images," *Proc. I.R.E.*, *28:* 458–468, 1940.
2. Pierre Mertz, A. D. Fowler and H. N. Christopher, "Quality rating of television images," *Proc. I.R.E.*, *38:* 1269–1283, 1950.
3. J. P. Guilford, *Psychometric Methods*, McGraw-Hill, New York, 1936; pp. 250–251.
4. M. Herzberger, "Light distribution in the optical image," *J. Opt. Soc. Am.*, *37:* 485–493, 1947.
5. F. H. Perrin and J. H. Altman, "Photographic sharpness and resolving power. II. The resolving-power cameras in the Kodak Research Laboratory," *J. Opt. Soc. Am.*, *41:* 265, 1951.

6. F. E. Ross, *The Physics of the Photographic Image*, Van Nostrand, New York, 1924; pp. 124–143.
7. G. C. Higgins and L. A. Jones, "The nature and evaluation of the sharpness of photographic images," *Jour. SMPTE*, *58:* 277–290, Apr. 1952; *PSA Jour.* (Phot. Sci. and Technique), *19B:* 55, 1953.

APPENDIX: Analysis of Variance, Sharpness Rank Numbers; 10 Observers, 6 Emulsions, 4 Test Objects.

Source of variance	Degrees of freedom	Sum of squares	Mean squares	Variance ratio	Components of variance	Standard deviation
Materials	5	546	109.2	91***	2.69	1.64
Materials × observers	45	31	0.69	1.53°	0.06	0.24
Materials × test objects	15	18	1.20	2.67**	0.07	0.27
Residual	174	78	0.45		0.45	0.67
Total	239	673			3.27	1.81

Because of the nature of the data used, there is no variability caused by the observers, by the test objects, nor by the observers × test objects. Therefore, the analysis can be considered a "doubly incomplete three-factor analysis: one factor with double-order replication." The degrees of freedom of the observers, the test objects, and the observers × test objects are pooled with the residual. The effect of changing the test objects is revealed by the material × test object interaction.

Random Picture Spacing With Multiple Camera Installations

By R. I. WILKINSON and H. G. ROMIG

When several high-speed cameras are operated simultaneously, but independently, it is possible that the aggregate of pictures obtained will satisfactorily cover the space between the pictures provided by any one camera. This paper gives a method for estimating the probability that the longest interval without a picture will not exceed a selected value.

Occasions arise when the rate of taking pictures with the fastest available motion-picture camera is insufficient to examine the characteristics of a rapidly moving object or phenomenon. One solution would be to synchronize two or more cameras out of phase so as to obtain suitably spaced pictures intermediate to those provided by a single machine. This would usually be an expensive and time-consuming procedure.

An alternative solution is to set up two or more high-speed cameras at the same location and operate them quite independently hoping that by chance from the aggregate of pictures so obtained a sufficiently "continuous" record of the sequence of events will result. What kind of coverage can be obtained by this procedure, and in particular what quantitative statement can be made regarding the adequacy of the coverage of the interval between the pictures provided by one camera? Since no particular subspacing of the pictures can be guaranteed with such a random timing arrangement, any description of the coverage must be made in terms of probabilities.

What, for instance, is the probability that with m cameras operating at random synchronization, there will be no more than c time intervals between pictures, which exceed a fraction, r, of a selected picture interval I of any one camera? How many cameras need be set up to provide a high degree of assurance that the longest picture spacing in such an interval will be less than i sec? How much improvement in the picture definition can be obtained by doubling the number of cameras? If the probability of finding no spacings greater than i sec is doubtfully acceptable, will permitting one interval to be as large as $2i$ improve the assurance sufficiently to give a satisfactory program? These and numbers of allied questions may be posed by

Presented on October 8, 1952, at the Society's Convention at Washington, D.C., by R. I. Wilkinson (who read the paper) Bell Telephone Laboratories, Inc., 463 West St., New York 14, and H. G. Romig, Hughes Aircraft Co., Culver City, Calif.
(This paper was received December 3, 1952.)
Ed Note: Due to the extensive nature of the discussion, the Chairman of the Board of Editors sought clarification and editing, a service which C. D. Miller has kindly performed.

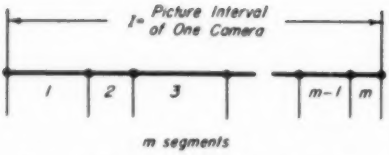


Fig. 1. Random division of a line in *m* segments.

those in charge of photographing very fast moving events. The theory of probability can give us their answers under certain simple assumptions as to the conditions of the experiment.

The most precise probability statements can be made in regard to the picture spaces which occur in some interval *I*, the length of the frame interval for a single camera. Such an interval can be chosen at random or designated by an event or criterion not depending on an examination or knowledge of the current picture spacing configuration. Certain useful conjectures can also be made concerning the picture spacings over a succession of *I* intervals. The limited first problem will be studied in considerable detail and followed by some comments on the more general situation.

Suppose *m* constant-speed cameras in random synchronization are taking high-speed pictures of some rapid phenomenon. In Fig. 1 the length of the heavy line is *I* sec and represents the time between successive pictures taken by camera No. 1. The picture instants of the other *m*-1 cameras might be as indicated by the heavy dots strewn "at random" along the length *I*. (The exposure time is considered to be short compared with the picture interval *I*.) We shall first determine the probability that none of the segments between the dots will exceed a length of *i* sec, and then solve the more general problem that exactly *c* segments will exceed *i* sec.

Imagine the picture interval *I* to be made up of a great number *n* of much smaller unit intervals, and that measured in these intervals, the permissible picture spacing *i* is *s* units long. Our problem now resolves itself into the geometrical one: When a line *n* units long is divided arbitrarily into *m* segments, what is the probability that exactly *c* segments will be *s* units long or longer?

A Mathematical Analogy*

Consider the possible composition of any one segment of the picture interval *I*, say the first one. Its length may conceivably vary from 0 to *n* units. (In the latter case all the other segments would have to have 0 length, since the total of all segments equals *n*.) Represent mathematically all the possible lengths of the first segment by the expression

$$x_1^0 + x_1^1 + x_1^2 + \ldots + x_1^n \qquad (1)$$

in which the *exponent* of x_1 indicates the number of units in the segment. Similarly the second segment's possible values can be represented by the same form of series, and the third segment, etc., up to the *m*th segment. We write them all down, as though they were to be multiplied together, as follows,

$$(x_1^0 + x_1^1 + x_1^2 + \ldots + x_1^n)$$
$$(x_2^0 + x_2^1 + x_2^2 + \ldots + x_2^n) \ldots$$
$$(x_m^0 + x_m^1 + x_m^2 + \ldots x_m^n). \qquad (2)$$

Next imagine all of the multiplications performed. After dropping the subscripts and collecting, the terms will range in degree all the way from Ax^0 to Wx^{mn}. Somewhere there will be a term of the form Hx^n, and it will consist of selections of *x*'s one from each series, such that the sum of their exponents always equals *n*. In fact all possible combinations of such selections will have been discovered in multiplying out the above product of series, and the

* The technique used here is known as that of generating functions. It was used in the solution of this problem for the special case of $c = 0$, by E. C. Molina of the American Telephone and Telegraph Co. in an unpublished memorandum of September 1, 1921.

number of such cases with exponents totaling n will be the *coefficient* of this x^n term. But this is also the number of ways in Fig. 1 that m segments could have been given values from 0 to n, such that their total was always equal to n. Hence the coefficient of x^n in the expansion of $(x^0 + x^1 + x^2 \ldots + x^n)^m$ will be the number of ways in which a line n units long can be divided into m segments.

The Mathematical Problem

The coefficient of x^n in $(x^0 + x^1 + x^2 + \ldots + x^n)^m$ will be the same as in $(x^0 + x^1 + x^2 + \ldots)^m$ in which the terms within the parenthesis do not end with x^n since the x^{n+1} and higher terms could contribute no cases to the final Hx^n term we are seeking. We then note that $(x^0 + x^1 + x^2 + \ldots)^m = (1 - x)^{-m}$. Expanding this binomial according to the rule for negative exponents, we have

$$(1 - x)^{-m} = 1 + mx + \frac{m(m+1)}{2!}x^2 + \ldots + \frac{m(m+1)\ldots(m+n-1)}{n!}x^n + \ldots . \quad (3)$$

Here the coefficient of x^n is

$$\frac{m(m+1)\ldots(m+n-1)}{n!} = \binom{m+n-1}{m-1} \quad (4)$$

where the lefthand side of Eq. (4) denotes the number of combinations of $m + n - 1$ things taken $m - 1$ at a time and the righthand side is a convenient notation meaning the same thing. This then is the total number of ways of dividing the line in Fig. 1 into m segments, with no restriction on the length of any one segment, the only requirement being that the lengths of the m segments add up to n.

Suppose we should now like to determine the probability that none of the m segments above is s units or longer. If we can determine how many "favorable" ways the line of Fig. 1 can be divided into m parts no one of which is longer than $s - 1$ units, the ratio of favorable to total ways will then produce the desired probability, $P_{m,0}$, that of m segments none will equal or exceed s in length.

To determine the number of favorable ways we proceed exactly as before representing each segment with a mathematical series, but now permitting no single series to go beyond the x^{s-1} term. The m series when multiplied together are then

$$(x^0 + x^1 + x^2 + \ldots + x^{s-1})^m, \quad (5)$$

and we have the problem again of finding the coefficient of x^n, the number of ways of dividing the line n units long into m segments no one of which is s or more units in length.

Expression (5) may be rewritten as

$$(1 - x^s)^m/(1 - x)^m = (1 - x^s)^m(1 - x)^{-m} \quad (6)$$

Expanding each of the latter two factors, gives

$$\left[1 - mx^s + \frac{m(m-1)}{2!}x^{2s} + \ldots + (-1)^k\frac{m(m-1)\ldots(m-k+1)}{k!}x^{ks} + \ldots\right] \times \left[1 + mx + \frac{m(m+1)}{2!}x^2 + \ldots + \frac{m(m+1)\ldots(m+n-1)}{n!}x^n + \ldots\right] \quad (7)$$

It may now be seen that the coefficient of x^n in (7), that is, the number of favorable ways, is

$$\frac{(m+n-1)!}{(m-1)!n!} - m\frac{(m+n-s-1)!}{(m-1)!\,(n-s)!} + \frac{m!}{(m-2)!2!}\frac{(m+n-2s-1)!}{(m-1)!(n-2s)!} + \ldots + (-1)^k\frac{m!}{(m-k)!k!}\frac{(m+n-ks-1)!}{(m-1)!(n-ks)!} + \ldots \quad (8)$$

$$= \frac{(m+n-1)!}{(m-1)!n!} \times \left\{1 - m\frac{(m+n-s-1)!}{(n-s)!}\frac{n!}{(m+n-1)!} + \frac{m!}{(m-2)!2!}\frac{(m+n-2s-1)!}{(n-2s)!}\frac{n!}{(m+n-1)!} + \ldots + \right.$$

$$(-1)^k \frac{m!(m+n-ks-1)!}{(m-k)!k!(n-ks)!(m+n-1)!} + \cdots \Big\} \quad (9)$$

$$= \frac{(m+n-1)!}{(m-1)!n!} \Big\{ 1 + \sum_{t=1} (-1)^t \binom{m}{t} \times \frac{(m+n-ts-1)!n!}{(n-ts)!(m+n-1)!} \Big\} \quad (10)$$

Then the probability sought is

$$P_{m,0} = \frac{\text{Favorable Ways}}{\text{Total Ways}} = \frac{\text{Equation (10)}}{\text{Equation (4)}} = 1 + \sum_{t=1} (-1)^t \binom{m}{t} \times \frac{(m+n-ts-1)!n!}{(n-ts)!(m+n-1)!} \quad (11)$$

Now if we imagine the line in Fig. 1 to be made up of such a very large number of units that n approaches infinity, then s likewise will approach infinity. We retain however the desired conditions by setting $s/n = r$ and requiring now that no one of the m segments should exceed the specified proportion r of the total length. With n and s approaching ∞ and $s/n = r$, the last fraction in Eq. (11), $(m+n-ts-1)!n!/(n-ts)!(m+n-1)!$, can be evaluated by Stirling's Theorem for factorials, and is found to be $(1-tr)^{m-1}$. Equation (11) can be rewritten more simply as

$$P_{m,0} = 1 + \sum_{t=1} (-1)^t \binom{m}{t} (1-tr)^{m-1} = 1 - \binom{m}{1}(1-r)^{m-1} + \binom{m}{2}(1-2r)^{m-1} - \binom{m}{3}(1-3r)^{m-1} + \cdots \quad (12)$$

in which the series extends for all values of t as long as $t < \frac{1}{r} < m$.

By a similar but slightly more involved procedure we can find the probability, $P_{m,c}$, that exactly $c = 1,2,3,\ldots$ segments of the picture interval I will have length ratios greater than r, while the remaining $m-c$ are all shorter than r. Thus

$$P_{m,c} = \binom{m}{c} \sum_{t=c} (-1)^{t-c} \binom{m-c}{t-c} (1-tr)^{m-1} \quad (13)$$

in which $(-1)^{t-c}$ insures the terms of the series alternate in sign.

The probability that not more than c segments exceed a length ratio of r, is found from

$$P_{m,\not> c} = \sum_{j=1}^{c} P_{m,j} = 1 - \sum_{t=c} (-1)^k \binom{t}{t-c} \binom{m}{t+1}$$

$$[1-(t+1)r]^{m-1} = 1 - \binom{c}{0}\binom{m}{c+1}$$

$$[1-(c+1)r]^{m-1} + \binom{c+1}{1}\binom{m}{c+2}$$

$$[1-(c+2)r]^{m-1} - \binom{c+2}{2}\binom{m}{c+3}$$

$$[1-(c+3)r]^{m-1} + \cdots . \quad (14)$$

Placing an added restriction on the problem, we may by a similar analysis write the probability $P'_{m,c}$ that c segments will exceed a length ratio r, but will not however exceed $2r$. Equation (13) then becomes

$$P'_{m,c} = \binom{m}{c} \sum_{t=c} (-1)^{t-c} \binom{m}{t-c} (1-tr)^{m-1} \quad (15)$$

Correspondingly, when *not more* than c segments are to be permitted to exceed a length ratio r (and none a length ratio of $2r$), we have from Eq. (15)

$$P'_{m,\not> c} = \sum_{j=0}^{c} P'_{m,j} = 1 + \sum_{t=1} (-1)^t \Big[\binom{m}{0}\binom{m}{t} - \binom{m}{1}\binom{m}{t-1} + \cdots + (-1)^c \binom{m}{c}\binom{m}{t-c} \Big] (1-tr)^{m-1} \quad (16)$$

Charts and Tables

The curves of Fig. 2 have been calculated from Eq. (12) for $P_{m,0}$, the prob-

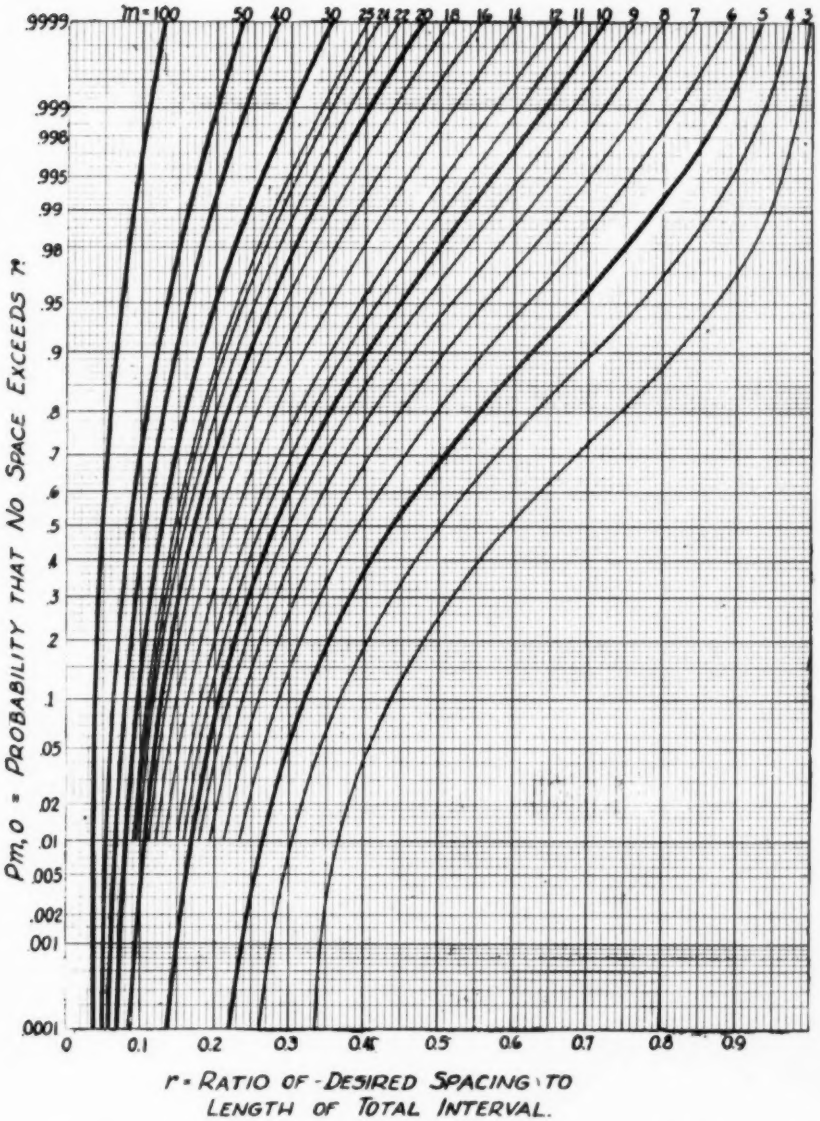


Fig. 2. Random spaces within an interval; number of cameras, m, required to provide assurance, P_{m0}, that desired spacing ratio, r, is not exceeded.

ability that no one of the m segments will exceed the specified proportion r of the total interval. Figure 3 gives the probability, $P'_{m,>1}$, that no more than one of the segments exceeds the proportionate length r, and if so is less than $2r$, and is calculated from $P'_{m,>1} = P_{m,0} + P'_{m,1}$.

From the curves of Fig. 2, Table I is constructed for ready reference. It gives the numbers of segments into which a line must be divided to obtain various assurances that all the segments will be shorter than any desired proportion of the line's total length.

Table I. Number of Segments (Cameras) Required to Yield an Assurance $P_{m,0}$ That No Segment (Picture Space) Exceeds a Proportion r of the Entire Line (a Selected Frame Interval).

$P_{m,0}$	$r = 0.2$	$r = 0.3$	$r = 0.4$	$r = 0.5$
0.90	26	16	10	7
0.95	30	18	12	9
0.99	39	23	16	11
0.999	50	29	20	15

Interpretation in Terms of the Camera Problem

If the motion-picture cameras employed jointly in taking photographs of a rapid phenomenon can be assumed to be operating substantially in random phase with one another, then the probability relationships derived above can be directly applied to any phenomenon of special interest which occurs so quickly as to fall within the picture interval time of one camera. This of course will not always be the case since one's interest may commonly extend over several, or many, framing intervals.

If by some feature of synchronous motor design, or other means, one could ensure only a small difference in the frame speeds of the several cameras employed (say less than 1%), it would by possible to extend a statement regarding one I interval to cover a period of such intervals, since successive intervals would repeat almost identical picture spacings. It is more likely, however, that the framing speeds of a group of cameras will vary quite widely, for example up to $\pm 10\%$ from a nominal value. Then with a limited number of cameras one I interval can hardly be considered as looking like its predecessor or successor, either actually or statistically, and a strong statement as to the probability of exceeding an allowable picture spacing *anywhere* in a short strip of several frames would be quite difficult to set down. However, for a period of only 2 or 3 frames, using cameras with no more than a few percent speed variation, it would seem likely that the picture configuration would not have changed so much but that one could usually apply usefully the single interval probability analysis; that is $P_{m,c}$ is approximately the probability that exactly c intervals in each frame exceed the permitted spacing.

Example 1. If 10 high-speed cameras, each having a picture rate of 5000/sec, are used in parallel to photograph a projectile striking a barrier, what is the probability that during the 0.2 msec following impact there will be no interval between pictures longer than $i = 0.0001$ sec? Here the picture interval for a single camera is $I = 0.0002$ sec. The ratio r of the permissible interval i to the whole interval I is $r = 0.5$. Entering the chart of Fig. 2, with an abscissa of $r = 0.5$, and reading up to the $m = 10$ curve, we find a point opposite $P_{m,0} = 0.98$. Thus we have an assurance of 98 chances in 100 that there will be no picture spacing among all those of interest which exceeds 0.0001 sec.

Example 2. Suppose in Example 1 only 5 cameras instead of 10 had been available. How much would the assurance have been lowered that the longest picture space would not exceed 0.0001 sec? Again consulting Fig. 2, we see the probability is reduced from 0.98 to 0.69,

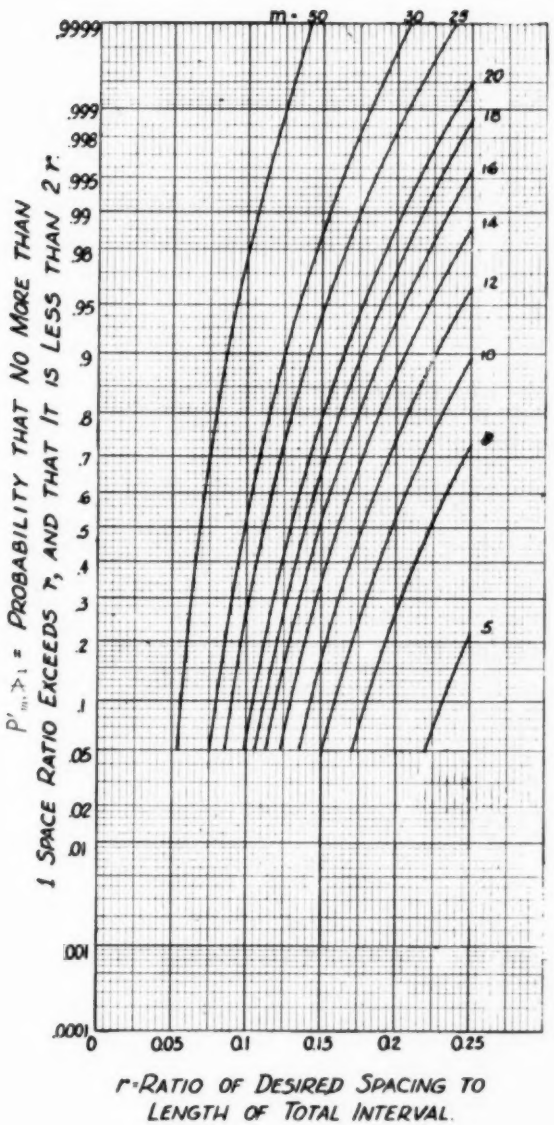


Fig. 3. Random spaces within an interval; number of cameras, m, required to provide assurance, $P'_{m,>1}$, that desired spacing ratio, r, is not exceeded by more than one case and that that case is less than $2r$.

which might not now be an acceptable assurance if it were highly important that *no* picture spacing exceed 0.0001 sec.

Example 3. In a certain type of explosion lasting about 0.01 sec, pictures are desired no further than 0.001 sec apart. Twenty cameras are at hand operating at 200 frames/sec. Will they be adequate to the requirements if operated in parallel with random synchronization? Here $r = 0.001/(1/200) = 0.2$, and from Fig. 2 we read that the probability is only 0.72 that all picture spaces will be less than the desired ratio. This would likely not give sufficient confidence of the scheme's satisfactoriness. We should perhaps then choose the minimum probability which would give us a feeling of confidence, say $P = 0.90$. With 20 cameras and this new assurance we find on Fig. 2 the corresponding r to be 0.24, which is only a little larger than the 0.20 originally specified, and might very well be a tolerated spacing since this is an *upper limit* (not exceeded with probability $P = 0.90$) to the largest picture space at the moment of explosion. Or, alternatively, permitting the interval ratio to increase to $r = 0.3$, would raise to $P = 0.977$ the assurance that none of the picture spaces exceeds this amount.

Example 4. Another alternative to the solutions of Example 3 is to retain $r = 0.2$ as originally proposed, but now permit one space ratio to be as large as $2r$, that is $r_1 = 0.4$, all other space ratios remaining less than 0.2. (This largest space ratio is not required to exceed 0.2, it merely may exceed it.) When the conditions are thus slightly relaxed, the probability of meeting them can be read from Fig. 3. In the present example, the assurance is 0.987, which is almost identical with that obtained when all ratios were allowed to go as high as $r = 0.3$. This information combined with the original assurance that 72% of the time all picture spaces of interest would be less than 0.001 sec ($r = 0.2$), might persuade us that the employment of 20 cameras here would be satisfactory.

If the event of interest covers a long strip of film, the analysis above can still be useful. With a number of cameras running at different speeds we may visualize that before very many hundreds of frames have been run off the aggregate of the I-intervals will have produced a variety of arrangements and lengths of picture spacings not unlike those comprising the "Total Cases" in the mathematical analysis above. Then we may interpret $P_{m,c}$ as not only the probability of a selected random I-interval containing c picture spacings greater than r, but also that of all the large number of I-intervals we should expect a proportion $P_{m,c}$ to have just c spacings greater than r. Furthermore, if $P_{m,0}$ is chosen close to unity (the usual case) the occurrence of more than one space exceeding r in the same I-interval will be rare; in which circumstance we may expect closely the proportion $\frac{1}{m}(1 - P_{m,0})$ of all the picture spaces in the film to exceed the length r, and the proportion

$$1 - \frac{1}{m}(1 - P_{m,0}) \qquad (17)$$

to be smaller than r.

Example 5. In photographing a rapid machine operation, how many cameras in random synchronization must be provided so that 99.9% of all picture spacings can be expected to be shorter than 0.2 of the single-camera frame interval? By trial in Eq. (17) it is found that $n = 31$ cameras yield $E = 0.999$. Since the value of $P_{m,0}$ involved here is close to unity (0.965), it may be assumed that most of the remaining probability is comprised by $P_{m,1}$ and the approximation of Eq. (17) will be satisfactory.

Finally there is the important case* in which an event of extremely short duration may conceivably fall in so long a picture space that satisfactory analysis of its character cannot be made. We here require the probability that a random point in time will fall in a picture interval greater than r. The solution involves weighing the probability of occurrence of intervals having 0, 1, 2 ... picture spaces longer than r by the probability that when such spaces occur, the random point will fall in one or another of these "long" spaces. The solution is readily obtained using an extension of the previous analysis.

The average length of a picture space of the "too long" variety, when it occurs, is required. The ways in which with m cameras a *single* space of length $z = s + k$ or longer can occur is given by the coefficient of x^n in the array,

$$\binom{m}{1}(1 + x + \ldots + x^{s-1})^{m-1} \times (x^{s+k} + x^{s+k+1} + \ldots). \quad (18)$$

Determining the ratio of favorable ways to total ways, and as before letting n, s and z approach infinity, with $s/n = r$, $z/n = j_1$, results in

$$P(\text{single space} \geqq j_1) = m\sum_{t=1}(-1)^{t-1} \times \binom{m-1}{t-1}[1 - j_1 - (t-1)r]^{m-1} \quad (19)$$

where the upper limit of t is the integral part of $(1 - j_1)/r + 1$. Then the relative frequency of occurrence of one "too long" space of length j_1 is

$$f(j_1)dj_1 = \frac{-dP(\geqq j_1)}{dj_1} = m(m-1) \times \sum_{t=1}(-1)^{t-1}\binom{m-1}{t-1} \times [1 - j_1 - (t-1)r]^{m-2} \quad (20)$$

* Called to the authors' attention by C. D. Miller of Battelle Memorial Institute.

And finally the average value of j_1 is

$$\bar{j_1} = \frac{\int_r^1 j_1 f(j_1)dj_1}{P_{m,1}} = \frac{1}{P_{m,1}}\sum_{t=1}(-1)^{t-1}\binom{m-1}{t-1} \times [mr(1-tr)^{m-1} + (1-tr)^m] \quad (21)$$

where the upper limit of t is now the integral part of $1/r$.

Similarly expressions for $\bar{j_2}, \bar{j_3}, \ldots \bar{j_i} \ldots$ can be obtained which give the average picture space when 2, 3, ... i, ... spaces exceed the permitted ratio r.* Then the total probability that the point-event will *not* fall in a "too long" space is

$$H = P_{m,0} + P_{m,1}(1 - \bar{j_1}) + P_{m,2}(1 - 2\bar{j_2}) + \ldots \quad (22)$$

In the usual case $P_{m,2}$, $P_{m,3}$... will be small, also $\bar{j_1} > \bar{j_2} > \bar{j_3} \ldots$, so that close upper and lower limits on H are, respectively,

$$\left.\begin{aligned} H_U &= P_{m,0} + P_{m,1}(1 - \bar{j_1}) + P_{m,2} + P_{m,3} + \ldots \\ H_L &= P_{m,0} + P_{m,1}(1 - \bar{j_1}) + P_{m,2}(1 - 2\bar{j_1}) + P_{m,3}(1 - 3\bar{j_1}) + \ldots \end{aligned}\right\} \quad (23)$$

Example 6. With varying numbers of cameras, from 20 to 50, operating at 5000 frames/sec, what is the probability that an event of extremely short duration will fall in a picture interval longer than 0.04 msec? Here $I = 0.0002$, $r = 0.00004/0.0002 = 0.2$. Solving for $\bar{j_1}$ in (21) and substituting in the two limit expressions of (23), yields the following values:

* It may be noted through geometrical consideration, that when $(1 - r)/mr$ is small, say less than 0.2, $\bar{j_i}$ is closely approximated by $r + \frac{1 - ir}{m}$.

Table II

m	$P_{m,0}$	$P_{m,1}$	$P_{m,2}$	$P_{m,3}$	f_1	H_U (upper limit to H)	H_L (lower limit to H)
20	0.723316	0.265169	0.011484	0.000031	0.24087	0.9361	0.9306
30	0.953738	0.046102	0.000160	—	0.22672	0.9895	0.9895
40	0.993356	0.006643	0.000002	—	0.22000	0.9985	0.9985
50	0.999108	0.000892	—	—	0.21600	0.9998	0.9998

The limits here are seen to specify very narrowly the desired probability H. In this example, if an assurance of approximately 0.99 is desired that the point should not fall in a space longer than 0.04 msec, 30 cameras need to be provided.

Acknowledgments

The authors wish to acknowledge the mathematical assistance of Mrs. S. P. Mead, and to thank Misses C. A. Lennon and A. G. Loe of Bell Telephone Laboratories for computing the curves of Figs. 2 and 3.

The numerous comments made by the discussions of this paper have added greatly to its interest and value. The authors are particularly indebted to C. D. Miller for his careful reading of the material and his comments on several points which were probably confusing and possibly misleading. We have attempted to clarify the presentation with the hope that the multiple camera method can be employed with but little likelihood of misapplication. Those shortcomings which remain are, of course, the responsibility of the authors.

Discussion

Richard O. Painter, (*General Motors Proving Ground, Milford, Mich., and Chairman of the Session*): At this time we will have any questions from the floor.

Kenneth Shaftan (*J. A. Maurer, Inc.*)*: My comments will constitute a discussion rather than a question. The authors have achieved a partial solution to the problem of complete coverage of various phenomena. Of course, one of the best approaches to the problem is to utilize some aspect of the phenomenon under study which can be recorded in some continuous manner. Then you are no longer worried about sampling rates. A consideration fundamental in a system such as that treated by the authors is the fact one must be able to arrive easily at a timewise correlation between the runs of different cameras. The man-hours being spent on this fundamental problem are tremendous.

The timewise correlation can be achieved directly by various systems of synchronizing cameras. Such a synchronization can be achieved at high frame rates. For example, let us consider the case of a camera wth a rotating prism having two plane surfaces. Two such cameras can be synchronized with the prisms 90 degrees out of phase. With 360 such cameras we could provide synchronization for each half degree of prism rotation, hence, 360 times the framing rate.

One of the most important considerations, though, is that of lashing down time in such a fashion as to establish the interval between frames exceptionally well for the individual camera, as well as this matter of synchronization from run to run, or camera to camera.

Mr. Wilkinson: You would certainly need a time trace of some sort that was appearing simultaneously in all of the camera films so you could lay the pic-

* The transcript of Mr. Shaftan's remarks has been edited by C. D. Miller after Mr. Shaftan's death, to provide this discussion.

tures alongside each other to test what distance camera No. 2, for example, was from camera No. 1.

Mr. Shaftan: That is the big problem.

Mr. Wilkinson: Apparently they have been able to do something along that line. I see Mr. Waddell, who used this technique, nodding his head. How he did it you will have to ask of him.

John E. Voorhees (Battelle Memorial Institute): In the example you cited, using several cameras in the photography of an atomic bomb explosion, what solution was chosen from this computation?

Mr. Wilkinson: The answer to that question cannot be revealed.

Dr. Schardin: You say it can't?

Mr. Wilkinson: I don't believe so.

[Discussions by H. Schardin and by C. D. Miller have been clarified and amplified at the request of the Chairman of the Board of Editors and appear below in the revised forms.]

Comments Solicited by the Chairman of the Board of Editors

Dr. H. Schardin (Laboratoire de Recherches, St. Louis, France): The object of a motion-picture series is to make possible an analysis of the space-time relations of a visible phenomenon after its occurrence. With most photographic equipment, the quality of resolution of space and time are mutually dependent. In other words a higher repetition rate is possible only through a reduction of image size. Here we are considering the question as to how an improvement of timewise resolution can be accomplished without change of the resolution spacewise.

An often-used method, propounded by the authors, is to increase the number of frames per second by the simultaneous use of a number of identical pieces of equipment. With this method, each apparatus photographs the subject on the same scale as if it were used alone. If n similar cameras are used, each with a repetition rate of approximately f_w, the average combined repetition rate may be expressed as nf_w. However, the quality of the timewise resolution is not then simply proportional to nf_w. It is instead proportional to $(g) \times (nf_w)^{3/2}$, where g is the resulting quality factor.* The quality factor g in this case is the ratio of the reciprocal of the repetition rate to the exposure duration of an individual frame.

If n cameras are used side by side, although the average repetition rate increases to nf_w, the average quality factor decreases to $\frac{g}{n}$. Hence, the timewise resolution is proportional to

$$\frac{g}{n}(nf_w)^{3/2} = \sqrt{n} \times gf_w^{3/2}.$$

The timewise resolution, therefore, is only $\sqrt{n}$ times as great as with the use of a single camera.

Conditions become essentially more favorable if, with the increase in number of cameras, the nature of the cameras is changed. The repetition rate is limited, among other things, by the frame height (not by the frame width). To obtain better timewise resolution, cameras can be used with a suitable n-fold reduction of the frame height. Such an arrangement allows an n-fold increase in repetition rate with an unchanged quality factor. In many cases, such an arrangement is simple to realize with prism apparatus.

The entire field is now no longer photographed by each camera. Instead, the individual fields of the cameras border each other. With n cameras the field of each camera corresponds to one nth part of the entire field. Yet the entire field is recorded with unchanged spacewise resolution. The timewise resolution is then proportional to

$$g(nf_w)^{3/2} = n^{3/2} \times gf_w^{3/2},$$

* See H. Schardin, *Schweizerische Photorundschau, 14:* p. 294 (1951).

which is better than in the previous case by the factor $\frac{n^{3/2}}{\sqrt{n}} = n$.

If cameras with an n-fold reduction of frame height but unchanged frame width are not available, the possibility can still be investigated of using suitable equipment with which the frame height and frame width are reduced in like degree. For example, 4 16mm cameras or 16 8mm cameras can be used in preference to 4 or 16 35mm cameras. By use of such narrow-film cameras, a timewise resolution is obtained proportional to

$$g(\sqrt{n}f_w)^{3/2} = n^{3/4} \times gf_w^{3/2}.$$

In comparison to n cameras using film of normal width, we then have an advantage in timewise resolution by a factor of $n^{1/4}$, as well as the further advantages of reduced area of film required by a factor of $\sqrt{n}$ and lower cost of the experimental equipment.

We are often not concerned with such material advantages, but only with increasing the accuracy of measurement to allow even the establishment of the existence of an effect that has been sought. It should be pointed out here that a fundamental advantage is offered, with the simultaneous use of a number of cameras, by the principle of subdivision of the field. With use of this principle, it is not of great importance whether the cameras are synchronized or not.

C. D. Miller (*Battelle Memorial Institute*): The authors have contributed a valuable service in providing a mathematical solution to the probability of capturing rapid events by a sampling technique.

As pointed out by Dr. Schardin, an increase in repetition rate with unchanged exposure duration for the individual frame is of considerably less value than a like increase in repetition rate accompanied by a proportional reduction of exposure duration. However, the nuances encountered in the application of this principle are quite remarkable.

The question of the desirability of a small ratio of exposure duration to interval between consecutive frames depends a great deal upon the purpose of the photographs. Ordinarily, if the purpose is to treat the individual frames as stills, and to make measurements of displacements from those stills, there is certainly nothing to be gained by having more exposures per second than the reciprocal of the exposure duration of an individual frame. Ordinarily there is even little to be gained in obtaining more than one-tenth that repetition rate.

On the other hand, if the purpose is to produce a motion picture for viewing on a projection screen, there is an advantage in increasing the number of pictures even beyond the reciprocal of the exposure duration. However, for this purpose, the increased number of pictures can be obtained in the process of reproduction from the original film, rather than by extending the repetition rate of the high-speed camera beyond the reciprocal of the exposure duration.

We took some photographs at NACA of the phenomenon of knock in a spark-ignited piston engine at 200,000 frames/sec, approximately the reciprocal of the exposure duration. However, when these photographs were projected at 16 frames/sec, the detonation wave which travels through the mixture at the time of knock was still too fast to follow readily by eye. So we printed those pictures, dissolving one frame into the next in the printing process, so that over a distance of five frames on the print we gradually changed from the first to the second frame that we had taken with our high-speed camera, over the next five frames we dissolved from the second frame into the third, and so on. By that method, we obtained a slow-motion picture which showed on the projection screen very distinctly a phenomenon that could not be seen when the original photographs were projected, and with no visible decrease in the spacewise resolution. Moreover, this result could not be obtained by

simply printing each frame of the original five times on the print. The effect of dissolving one frame into the next was essential. Moreover, this method of slowing down the motion picture by multiplication of frames in the printing process would probably not be successful if the repetition rate of the high-speed camera were substantially less than the reciprocal of the exposure duration.

Essentially, all information obtained from high-speed photographs consists of determination of spatial velocities at various instants of time. A rate determination, of course, consists of a distance divided by a time interval. In such determinations from high-speed photographs, the distance used is proportional to the reciprocal of the repetition rate. The degree of accuracy of the determination of this distance, however, varies inversely with the exposure duration. Hence, as the exposure duration is increased relative to the reciprocal of the repetition rate, the accuracy of the determination of distance, and hence the accuracy of the determination of rate, diminishes.

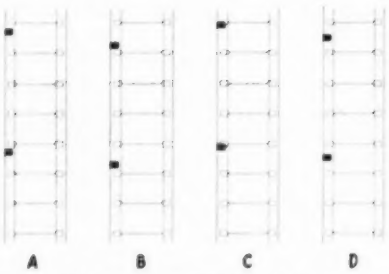
A rate determined upon the basis of the distance moved between the exposure of two successive frames must, of course, be an average rate for the movement between the exposures of those two frames. The rate at any instant between the two exposures may be treated as approximately equal to the average rate throughout the interval between the two exposures. Better, a curve may be constructed from average rates determined for the intervals between a large number of consecutive frames, and the rate for any instant of time may be read from the curve so constructed.

Even the second procedure is only approximate. Hence the desire to obtain more accurate determination of rates for several chronological points between the exposures of successive frames, by the exposure of additional frames throughout the interval. However, as we increase the number of exposures without decreasing the exposure duration, we encounter this problem of diminishing accuracy. Unfortunately, as we reach the value of repetition rate equal to the reciprocal of the exposure duration, the accuracy of the rate determination diminishes to about the same value as would be determined by a curve constructed from photographs taken at a lower repetition rate.

Problems exist, however, for which the foregoing reasoning does not apply, even when the photographs are used as stills for measurements. An example would be a hypothetical event in which an object becomes intensely luminous within an interval of perhaps one microsecond or less. In such a case, it might be desired to determine the exact time of development of luminosity. The luminosity might be assumed to be so great as to produce a dense exposure on the photosensitive film within one microsecond. Under these conditions, assuming an exposure duration of one millisecond provided by an individual camera, and assuming an infinitely quick cutoff of the exposure in each camera, Camera *A* might photograph the luminosity during the last microsecond of its one-millisecond exposure, whereas Camera *B*, phased one microsecond later than Camera *A*, would miss the development of the luminosity entirely. In such a case, great value might result from an increase in repetition rate far beyond the reciprocal of the exposure duration, if means were provided for a sufficiently accurate determination of the relative phasing of the cameras. Also, in this case, Dr. Schardin's quality factor would not apply in any simple manner.

John H. Waddell (*Wollensak Optical Co.*): I would like to present the two primary reasons for inviting the authors to give this classic paper on the application of random sampling to high-speed camera operation.

(1) Field Operation. Oftentimes it is necessary to round up or to use equipment which is readily available, and to



Discussion Fig. 1. Timing pips in four films; time separation, 1 msec. Order in which films would be read or printed: (1) C, (2) A, (3) D and (4) B.

get the best results for a minimum number of dollars. The questions one asks first are: How portable is the equipment, and is it easy to set up and to use?

It is conceivable to set up a synchroselsyn system for camera operation which would cost a million or two million dollars, and would require two or three years to develop and another six months or a year to train a crew to operate the system. Furthermore, such a system has a complex operating mechanism which requires top-flight engineers to set it up and to maintain it.

It is also possible to design and build single cameras to perform such a task—but where is a camera system which can possibly photograph up to x number of camera times 4000, 16mm pictures, or 8000, 8mm pictures times the fraction of a second that it takes the 100-ft lengths of film to be taken with a synchronizing time signal of 0.001 in. on all films? The high repetitive rate cameras are either bulky (may weigh up to 4 tons), do not have the desired time cycle, or their resolution is not as much as desired.

Furthermore, it is often desirable to design completely a complete operating photographic system in as little as two weeks, and not two years.

(2) Interpretation of Results. The films obtained can be either projected or read frame by frame.

Typical timing marks with respect to frame positions for four cameras are shown in Discussion Fig. 1.

In frame-by-frame analysis, the timing can be considered linear between any two timing marks, since the change in slope on acceleration or in steady state is negligible and below the limits of experimental error. With the same signal from the master oscillator being placed on all the films, and with zero time starting after the cameras are moving, the counting is a comparatively easy task.

As far as the motion-picture record goes, there is an accepted practice in printing in which a single frame can be printed in any multiple desired (as the 24 frames of the Schardin picture which were printed about 5 times each to get a long record), or the frames from different negatives can be printed on a single film by skip printing the positive. In the optical printer, there must be some means available for checking the negative registration.

I believe this paper is of fundamental and classical importance, and is an unbiased, extremely valuable contribution to the science of high-speed photography.

High-Speed Photography in the Chemical Industry

By W. O. S. JOHNSON

The du Pont Company's Mechanical Development Laboratory has made use of high-speed photographic techniques in the evaluation of chemical, metallurgical and mechanical processes. To cover the wide range of subjects encountered, some development work on cameras, lights and associated equipment has been necessary. This work is described herein.

THE Mechanical Development Laboratory of the du Pont Company's Engineering Department purchased its first high-speed photographic equipment, a Western Electric Fastax 16mm camera, in 1946 after a series of successful pictures had been taken for it by an outside consultant firm. These pictures covered the early stages of the development of a new autoloading shotgun, in cooperation with the Remington Arms Co., and showed clearly the accomplishments possible in the field of high-speed motion analysis. Following these early pictures, every design change on the new gun was assessed by means of high-speed photography. The action of each latch, spring and lever, and the effect of high- and low-velocity shells on the mechanism were the subject of numerous pictures.

Presented on October 9, 1952, at the Society's Convention at Washington, D.C., by W. O. S. Johnson, E. I. du Pont de Nemours & Co., Inc., Mechanical Development Laboratory, 101 Beech St., Wilmington, Del.
(This paper was received Sept. 21, 1953.)

In connection with the development of a safety device for a black powder wrapping machine, it was necessary to determine the flame-propagation speed of the particular type of powder being handled and then to develop a suitable guillotine-type door which would seal off the entry and exit ports to the room containing the machine. In this operation, unwrapped black powder pellets are fed to the machine in a continuous stream on a belt conveyor. After tests were run to determine the flame-front velocity of the stream of powder, a photocell-triggered gate was developed and tested. High-speed pictures of this gate revealed all the critical factors:

(1) the triggering electronic circuit performed satisfactorily;

(2) the water spray preceded the blade in its downward travel;

(3) the blade closed within the desired interval (actual stroke duration less than 10 msec);

(4) the deceleration pads operated as planned; and

(5) the flame was completely stopped at the barrier even though a solid powder

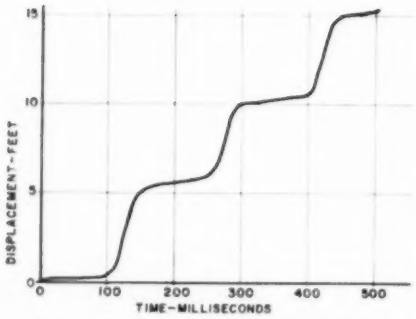


Fig. 1. Curve showing flame front travel in train of unwrapped black powder pellets.

line had existed through the opening and the condition of the powder dust typical of the operation was simulated as nearly as possible.

A time-displacement curve of the powder flame front is shown in Fig. 1.

Next, the assistance of high-speed photography was requested in connection with one of the Company's textile fiber packaging operations. To obtain the type of information needed, it was necessary to develop some method of frame-by-frame analysis from which time-displacement curves could be plotted for the elements under investigation. A Bell & Howell Filmosound projector was purchased and fitted with suitable handcrank and frame counter. A heat-reducing filter of sufficient cooling capacity permitted the examination of any single frame for an unlimited period. A projector so equipped can now be purchased as a standard item. This unit proved invaluable in the textile studies, all measurements being made directly from the projected images. A vertical drawing board equipped with a drafting machine was used as a projection screen because of the large number of measurements required. It was found that this arrangement facilitated the measurement of angular rotation as well as linear dimensions, the straight edge being laid tangent to a line on the image and the angle read directly and accurately, regardless of change in position of the rotating member in the field from frame to frame.

One problem which became evident as the use of the high-speed camera was extended, particularly in the textile field and in the study of sprayed materials, was the need for improved time resolution. The Fastax camera as manufactured has an exposure ratio of 1 to 3; that is, at 5,000 frames/sec the exposure duration is 1/15,000 sec, or 66 μsec. In photographing filament action in many yarn-handling operations, calculations showed transverse filament velocity in terms of filament diameter to be high enough so that blurring of the image of the filaments would occur during the 66-μsec exposure. Test runs corrobated these conclusions. Since the rear opening in the camera's aperture box (the stationary box around the rotating prism) serves as the optical equivalent of a focal-plane shutter, it appeared that by varying the vertical height of the opening, the exposure duration could be adjusted independent of the frame rate. Three additional aperture boxes were fabricated, one having a rear aperture one half the normal height; one, one-quarter the normal height; and one having an opening 0.010 in. wide. Using these, exposure durations of 33, 17, and 4 μsec, respectively, were realized at 5,000 frames/sec with some loss in frame height. In order to maintain full frame height, it was necessary to widen the front opening of each aperture box slightly.

A marked reduction in motion-produced blurring was accomplished (Fig. 2); however, the time distortion common to all focal-plane shutter cameras was noted. Of course, a proportional increase in light intensity was necessary.

In order to effect the split-second synchronization of light, camera and

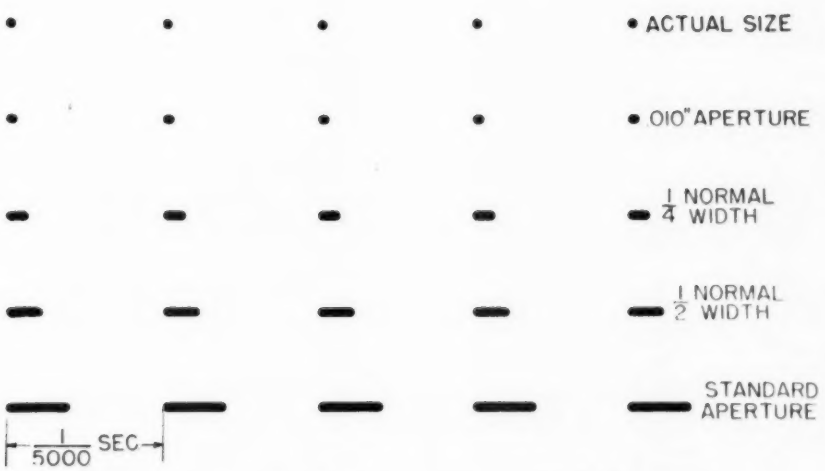


Fig. 2. Appearance of small sphere traveling at 100,000 diameters/sec with various apertures — several consecutive frames superimposed.

subject so often necessary to this work, an overall sequence controller, developed by the Remington Arms Co. for its own use, was adapted with minor modifications. This device controls the operation of the lights, the camera, and single or multiple operation of the event wherever this can be accomplished electrically.

In order to take advantage of the improvements recently incorporated into the Fastax camera, namely the high-resolution prism and the bright-field viewfinder a new 16mm Fastax was purchased. The prism of the original Fastax has been removed in order to provide a high-speed streak and oscillographic camera, which, with the aforementioned aperture boxes, is capable of a time resolution of 2 to 4 μsec. In the study of impacts, for example, it can provide more complete information than any standard frame-type camera since a normal camera sees the object being viewed for but a fraction of the total time, while a streak camera views the object continuously during the taking cycle. Figure 3 is the streak image of a punch as it is struck by a dropping hammer.

An Edgerton high-speed stroboscope was purchased to provide microsecond time resolution without the intense heat produced by the incandescent sources normally used. Many of the operations about which we are most concerned are strongly affected by ambient temperature. The presence of a hot body in close proximity to the operation is often required to provide sufficient light and in several instances has caused a complete breakdown of the process being investigated. This has been particularly evident in research on the mechanism of spinning of synthetic fibers.

In connection with this same research, lens equipment was needed which would provide greater flexibility than those normally supplied with the Fastax camera. We had already obtained the standard complement of lenses including the 25-, 35-, 50- and 104-mm lenses and had built lens extension barrels to permit focusing these lenses at shorter distances than those for which they were normally rated. Due to the unique

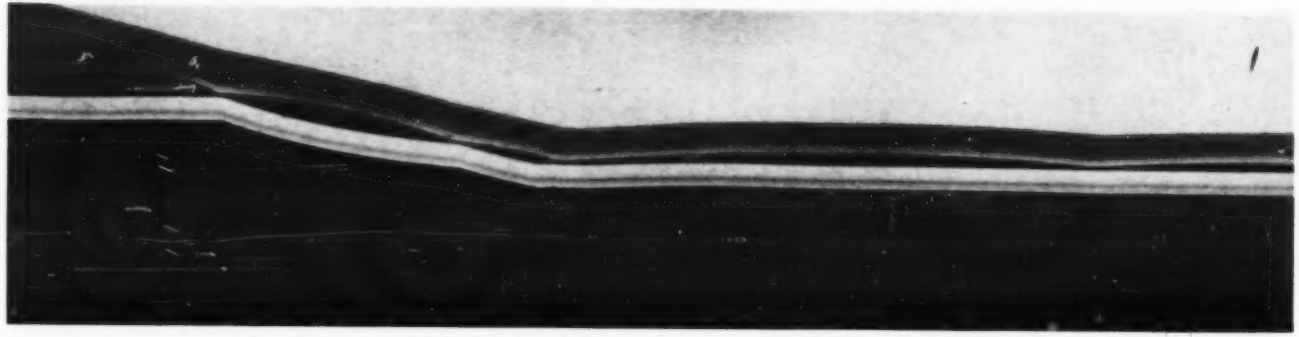


Fig. 3. Streak image of punch displacement.

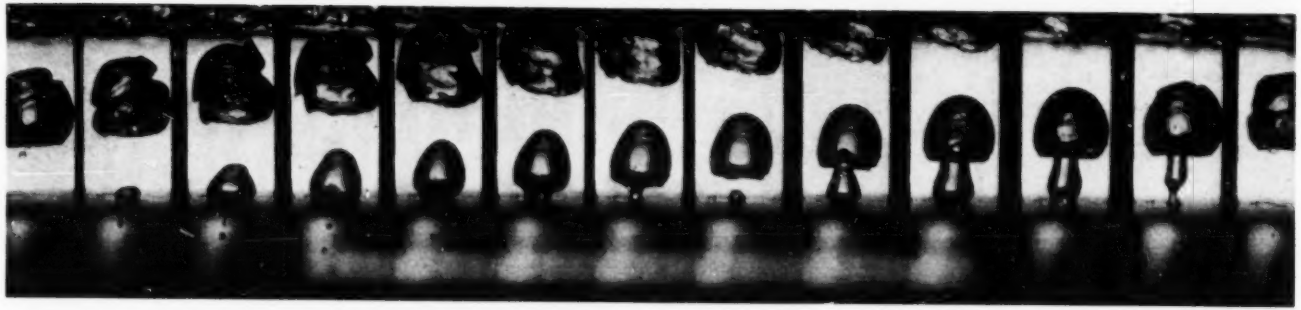


Fig. 4. Sequential stroboscopic pictures of bubble formation in water.

construction of the bayonet lens mount, however, a dead spot existed for each lens since the minimum thickness of the adapters was 5/16 in. This was considerably greater than the total focusing excursion of any of the above lenses. In order to overcome this difficulty, we obtained 48-mm and 72-mm Micro-Tessar lenses and fabricated slip-tube adapters by means of which the lenses could be focused at any film-to-subject distance. These lenses have been used with marked success in microscopic high-speed photographs of individual filaments at magnification ratios up to 5 to 1, field width being less than 1/10 in. The lenses have also been used successfully in macrophotography.

A Sept 35mm camera was purchased and altered to provide a continuously moving film camera which could be used for streak or oscillographic photography. In addition, it has been used in many instances with the Strobotac-Strobolux combination for taking motion pictures of action so slow that the use of regular high-speed equipment was thought to be unnecessary. In this connection, it was found that two or more Stroboluxes may be triggered by a single Strobotac and that by using this arrangement satisfactory pictures of many subjects may be taken. Figure 4 is an example of the use of this technique in studying bubble formation. The operation of bubbling vapors through liquids as a method of accomplishing transfer of either liquid or gas components is a basic operation in many chemical processes. The purpose of the study was to obtain data relative to the effect of bubble rate, gas density and viscosity, liquid density and viscosity, surface tension, hole size, etc. Simultaneous high-speed pictures and dynamic pressure records were taken in many cases.

In addition to the necessarily abbreviated examples presented here of applications of high-speed photography at the du Pont Company's Mechanical Development Laboratory, the technique has been used in the investigation of almost every phase of textile manufacture, from the spinning of a single filament to the sewing of finished fabrics; in the study of paint spraying; in metallurgical studies; and in the investigation of fundamental chemical processes. It has also been used to study the effect of explosions.

High-speed photography has proved to be a valuable research tool; however, our many investigations have shown that there is an enormous field which present equipment does not cover. We are looking forward to the time when picture rates many times in excess of what is now possible will be commonplace.

Full-Frame 35mm Fastax Camera

By JOHN H. WADDELL

A full-frame 35mm rotating-prism type camera is described and its features discussed. The camera has a 500-ft capacity and a picture-taking rate of from 100 to 2500 frames/sec.

HISTORICALLY, five major 35mm full frame high-speed motion picture cameras have been designed. Jenkins designed one employing a rotating-lens system, later Zeiss and then Wyckoff and Partsch designed a camera using the same principle. Edgerton built one synchronized with flashing high-voltage gas-discharge tubes. Chesterman and Myers designed one using a rotating prism. And there have been several other single cameras, built for specific purposes, some of which used rotating mirrors.

Rotating-Lens Cameras: Herbert Grier, of Edgerton, Germeshausen and Grier, stipulated that measurements from high-speed camera films be accurate to $\frac{1}{10}$ of 1%. It is almost impossible to find 20 or more matched lenses for a rotating-lens camera whose focal length can be maintained to give films within the $\frac{1}{10}$ of 1% requirement, under varying conditions of temperature.

Rotating-Mirror Cameras: These are potentially better but the film drive is rather complex. The optical performance of mirrors is an attractive argument in their favor.

Cameras Using Synchronized High-Voltage Flashtubes: In a camera with no shutter, the flashtube must fire very fast, for reasonably high picture-taking rates. The resolving power desired in cameras today must be better than 50 lines/mm, or the individual line would be 0.01 mm or 0.0004 in. To assure good image quality with a moving film, this film should not move more than 0.0002 in. during exposure. The study of the effect of film velocity versus time of exposure to obtain this quality is:

Time of flash (μsec)	Velocity of film to get 0.0002-in. smear (ips)
1	200
10	20
100	2
1000	0.02

It is to be noted that the high-voltage lamps, when used in conjunction with

Presented on May 1, 1953, at the Society's Convention at Los Angeles, by John H. Waddell, Industrial and Technical Photographic Div., Wollensak Optical Co., Rochester 21, N.Y. This paper was scheduled in the International Symposium on High-Speed Photography held at Washington, October 1952.
(This paper was received October 8, 1953.)

image-compensating type cameras, produce images of the highest possible resolution.

Rotating-prism cameras have been manufactured and used extensively in the 8mm, double-width 8mm, 16mm, and half-frame height 35mm frame sizes. They all have one deficiency, and that is that no satisfactory enlargements can be made on full-frame 35mm film for large-screen projection. On a 16mm film which had 50-lines/min resolution, a 35mm enlargement from the 16mm film has only 20 lines/mm, which does not give good results when projected when compared with films taken on an intermittent camera.

The film capacity of the commercially available cameras was too small, also. Longer runs were desired.

Realizing the need for a 35mm large capacity high-speed camera, the Government of the U.S.S.R. requested the Western Electric Company to design and build such a camera in 1945.

In an earlier paper,* certain suggested improvements of design were discussed. The first of these was prism design, and second, the design of the sprocket.

The full-frame 35mm Fastax now being introduced has the experience of eighteen years of rotating-prism cameras behind it.

The design features and specifications of the new camera are as follows:

Camera Housing: To reduce weight, a magnesium-aluminum casting will be used. It will be heavy enough to withstant high-blast pressures. Parts will be mounted to withstand at least 20 "g" acceleration. The camera housing will enclose the drive mechanism and lens mount, and will be fitted with standard motion-picture threads for mounting on standard motion-picture tripods.

Sprocket: A sprocket of approximately 6-in. diameter is employed. The curvature of this sprocket face very nearly matches the change in back focus created by the oblique rays as they pass through the prism. Since 35mm negative and color stock in the United States is on slow-burning base, the sprocket is designed to take ASA standard negative perforations. A 180° wrap is used as has been the case on previous Fastax cameras. The sprocket is light in weight and is black to prevent halation and reflections from the inside of the sprocket through the viewing holes when an intensely bright self-incandescent subject is photographed.

Film Capacity: 500-ft, special daylight-loading spools have been designed to ensure maximum acceleration and to permit better balancing of the shifting load. The jump at the beginning and the end of the films is minimized. These spools are inclosed in detachable magazines. Each magazine comes supplied with a motor for the take-up. The film is used on spools so as to keep it in place under conditions of vibration and when high centrifugal force is present.

Prism and Housing: The prism is made from Eastman Kodak 450 glass and is four-sided. The housing is very much heavier than on any previous Fastax cameras. It, too, is designed to provide better chopping action of the image. The prism housing is supported by an outboard bearing to make the pictures more steady. The half-frame 35mm-Fastax employs the same method, and that camera has been noted for its steadiness. There is no provision for removing the prism for oscilloscopic purposes, for it has been found that, with the very tight tolerances of fits and adjustment of gears, jumping pictures result from removing the prism housing.

* John H. Waddell, "Design of rotating prisms for cameras," *Jour. SMPE, 53:* 496–501, Nov. 1949 (also in *High-Speed Photography,* vol. 2).

Fig. 1. Front view of the full-frame 35mm Fastax Camera.

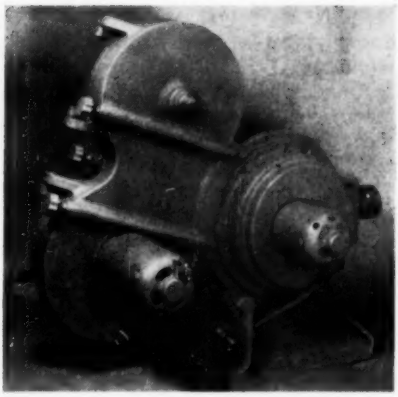


Fig. 2. Rear view, showing adjustable torque feed spindle and motor.

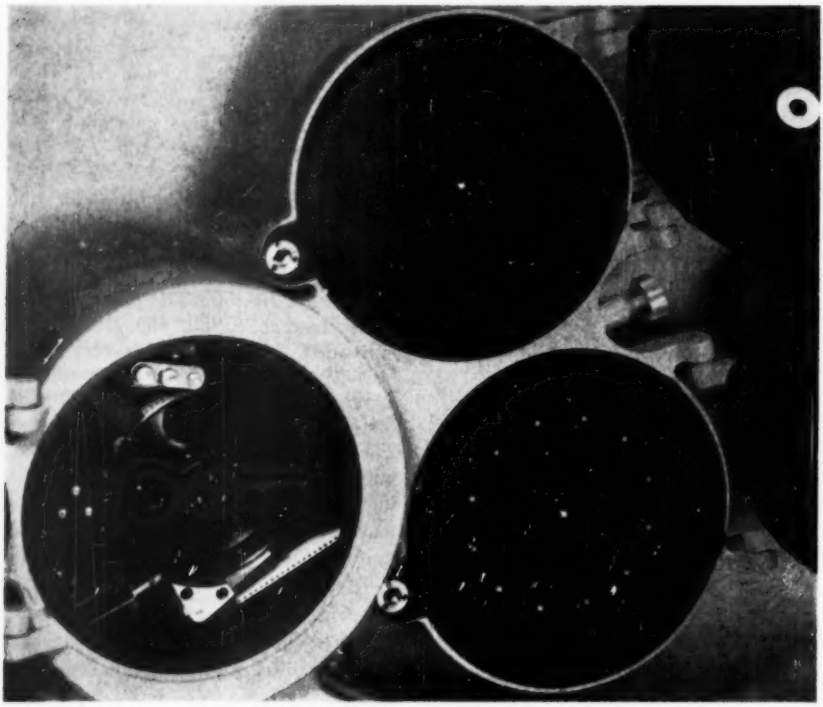


Fig. 3. Interior of camera.

Motors: Universal a-c/d-c type whose speed is dependent on supplied voltage. For isolated field use, storage or hot-shot batteries will operate the camera. Standard a-c (50- or 60-cycle) can be used in the laboratory.

Prism Drive: Simple gear train with ultra-precision gears. The ratio of the driving and pinion gears is one to six.

Lenses: A 4-in. $f/2.3$ lens will be standard on the camera. As has been pointed out, higher overall resolution is obtained with longer focal length lenses. The light is traveling in a more parallel beam. Other lenses available will be:

1-in. $f/2.3$*
35mm $f/2.3$*
2-in. $f/2.3$*
3-in. $f/2.3$
6-in. $f/2.7$
10-in. $f/4.5$
24-in. $f/5.6$
40-in. $f/7$
80-in. $f/7$

(* Use only with fiducial marking attachment.)

Feed Spindle: Torque adjustable so that as film speed is altered, best results can be obtained through minor adjustment.

Timing Light: Double lamps provided. One can be used for standard time flash, and the other for event flash. NE66 lamps are used. It has been found that 135 volts will give better results with these lamps.

Viewfinders: Bright field telescopic and tracking finders will be provided.

Modifications to the camera to fill specific user needs will be made on request and to specification.

A camera of this type has long been needed in this country. In designing this camera a large number of factors have been taken into consideration. It is rugged and easy to manipulate. Its good picture quality fills the needs of research and development laboratories, the field, and the newcomers to high-speed photography, producers of entertainment and television.

Primary Color Filters With Interference Films

By H. H. SCHROEDER and A. F. TURNER

A set of vacuum-deposited thin-film multilayer transmission filters has been developed for use as highly efficient primaries in additive color projection. Light which is not transmitted is reflected. Consequently the filters can be used in high-illumination beams without overheating and changing color. Modification of spectrophotometric curves can be effected as desired in specific problems.

THROUGH THE USE of vacuum-deposited multilayer interference films it is now possible from a practical and useful standpoint to design and manufacture transmission filters capable not only of supplanting colored glasses or gelatin in many cases, but also of producing color to specifications impossible with these older types of filters. Particularly the filters discussed herein correspond in hue to the Wratten three color projection primaries (Kodak Wratten Filter No. 47, blue; No. 59, green; No. 24, red). The Wratten filter curves are seen in Fig. 1 with theoretical curves of the interference coatings shown in Figs. 2a and 2b, illustrating two types of green-transmitting filters. The new filters are suitable for use as highly efficient primaries in additive color projection.

Presented on October 8, 1953, at the Society's Convention at New York by H. H. Schroeder (who read the paper) and A. F. Turner, Bausch & Lomb Optical Co., Rochester 2, N. Y.
(This paper was received August 31, 1953.)

Generally the filters are composed of alternating high- and low-index optical films deposited on a suitable substrate such as glass. Depending on particular requirements these types may have as many as 15 alternating layers. Through appropriate design and control of the relative thicknesses of the individual films predetermined optical specifications of wavelength and transmission may be achieved.

The materials used are all colorless, forming transparent films with practically no absorption in the visible and infrared. In the filters themselves reflectance plus transmittance totals 100% with the reflected portions being unused in the applications described.

In order to provide the best description of the properties of the filters from an engineering viewpoint a set of engineering spectrophotometric curves has been prepared, Figs. 3, 4, 5 and 6. These are based on actual experimental curves but have been simplified by smoothing so that nonessential irregularities are elimi-

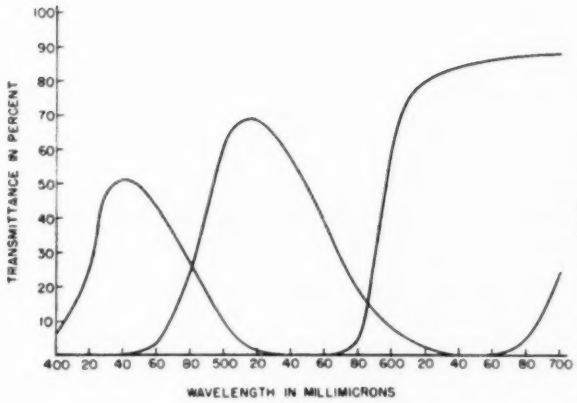


Fig. 1. Wratten three-color projection primaries.

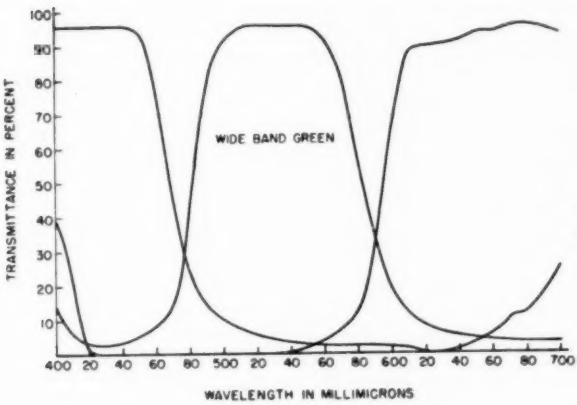


Fig. 2a. Multilayer interference coatings (theoretical curves).

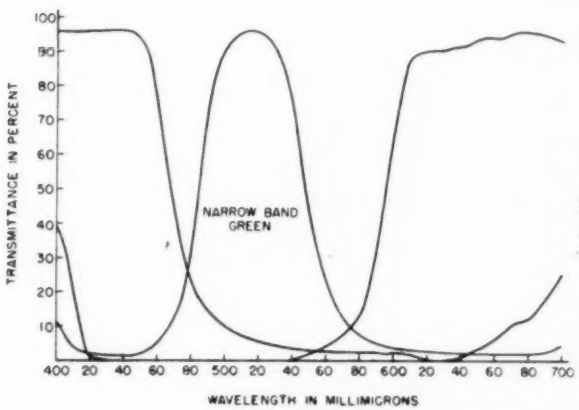


Fig. 2b. Multilayer interference coatings (theoretical curves).

nated. They will fit an experimental filter curve everywhere to within ±5%, exclusive of the background regions where the values shown represent maximum transmittances to be expected. This type of curve is considered to be sufficiently accurate for practical engineering purposes and has the advantage of simplicity of representation.

The blue-transmitting type is characterized in Fig. 3 by a maximum transmittance of 85% in the passband and a rejection-band transmittance of 2.5%. The degree of cutoff sharpness is described in terms of percent change in wavelength in progressing from the maximum transmission value to the first break in the curve in the low transmission region. Thus the blue has a cutoff factor of 6%. A slow rise in transmittance at the red end of the spectrum is attendant.

Figure 4 gives the characteristics of the wide-bandgreen-transmitting filter having a maximum transmittance value of 87.5%, rejection-region transmittances of 2.0 and 2.5% respectively for the blue and red, and cutoff factors of 4.5 and 5.5% for short and long wavelengths respectively.

The features of the red-transmitting type are illustrated in Fig. 5. The curve has 90% transmittance in the window, a drop to a value of 1% in the rejection part of the spectrum, and a cutoff factor of 9%. There is a sharp rise in transmittance at 420mμ to a value of 55% which extends to 400mμ.

In Fig. 6 the narrow-band green type is described. This filter involves a different film combination with a window transmittance comparable to that of the wide band but of less width at the top. There is a background value of 2% for both rejection regions which extends for the most part to the limits of the visible spectrum.

The two types of green filters discussed are indicative of what one may expect in the way of flexibility from multilayer interference coatings. In the same manner in which a design change brought about a change in width from one green filter to the other, one could readily change the type of film combination to effect more gradual cutting filters for the blue and red types. By changing thicknesses in the existing types, shifts to longer or shorter wavelengths to obtain different color characteristics can be achieved. The degree of sharpness in the cutoffs of the filters shown is obtained through the use of a limited number of layers, in this case fifteen. Sharper cutting types involving more films can be designed if desired.

In the chromaticity diagram of Fig. 7 the multilayer primaries define the color triangle shown, with the Wratten filters indicated by the triangular points. The Wratten filters show a greater saturation for the blue and red, while the multilayer green-coating saturation is slightly greater than that of the Wratten.

Also indicated in Fig. 7 is a definitive point for the narrow-band green which has a brightness slightly higher than the Wratten green with considerably more saturation.

In all cases the brightness values of the multilayer filters are above those of the Wratten filters, being approximately 60% greater for the blue, 71% more in the case of the green, and 6% more for the red. Colorimetric data comparing the two types of filters are shown in Table I.

Table I. Colorimetric Data—Multilayer Interference Coating vs. Wratten Filter

	Dominant λ-mμ			Purity (%)			Brightness (%)		
	Blue	Green	Red	Blue	Green	Red	Blue	Green	Red
Multilayer	446	542	614	89.7	65.6	88.0	4.1	59.1	17.1
Wratten filter	463	539	611	97.0	63.5	100.0	2.5	34.5	16.1

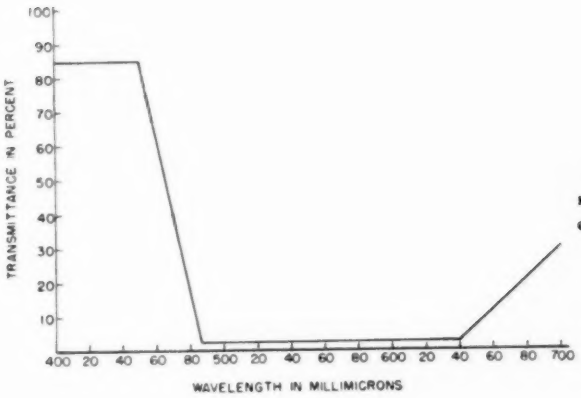


Fig. 3. Blue transmitting filter (engineering curve).

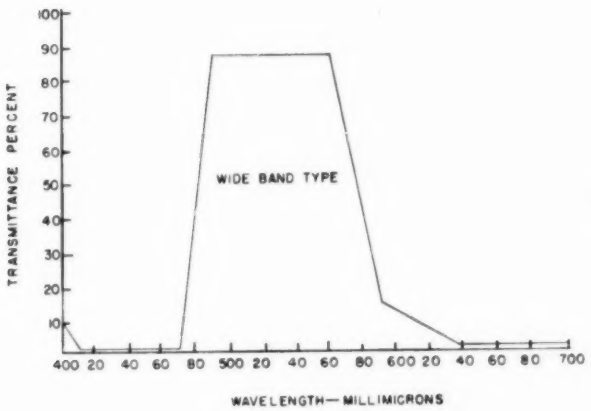


Fig. 4. Green transmitting filter (engineering curve).

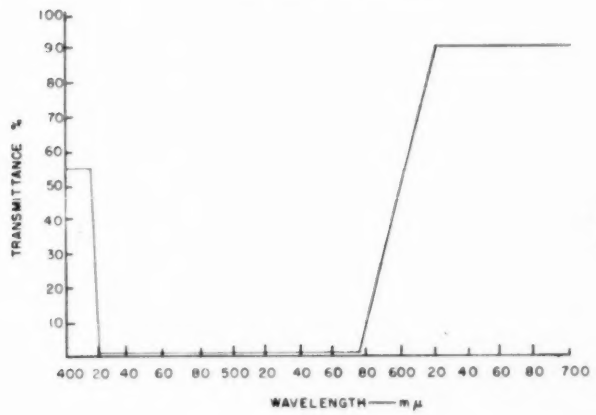


Fig. 5. Red transmitting filter (engineering curve).

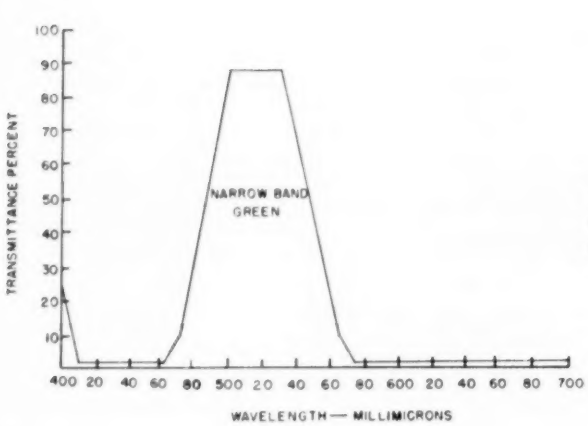


Fig. 6. Green transmitting filter (engineering curve).

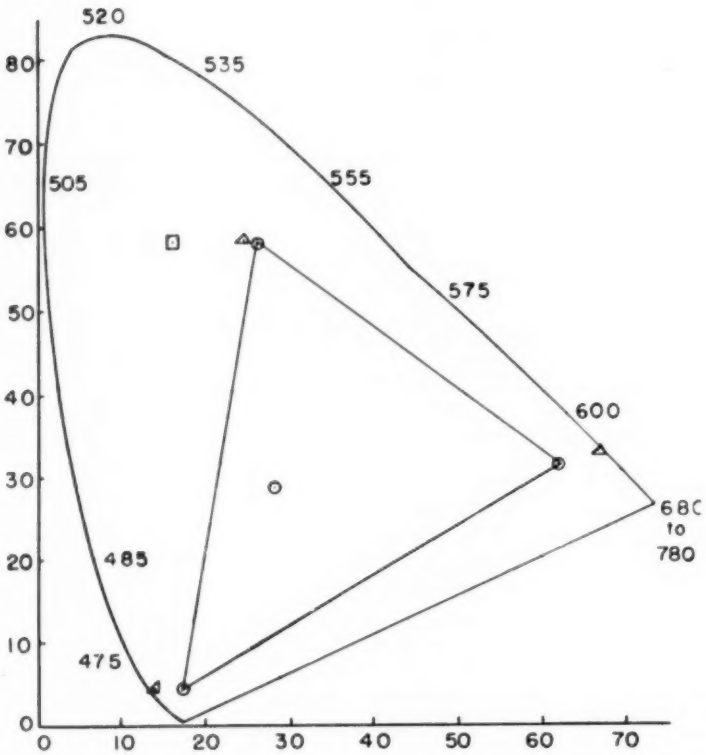


Fig. 7. Chromaticity diagram: ⊙ = multilayer interference coatings △ = Wratten filters ⊡ = narrow-band green filter.

One of the most important features of the vacuum-deposited multilayer interference coatings is their stability with respect to color shift upon aging, or exposure to elevated temperatures, whereas glass or gelatin filters are prone to fade or shift hue. This feature has proven itself under actual operating conditions in high-intensity projection equipment.

The coatings can be readily cleaned of smudges and fingerprints with a clean soft cloth or washed in a detergent solution followed by rinsing and drying with a clean soft cloth. Should abrasive particles be present scratches may occur in the film, but no general breaking down of the coating which would affect the function of the filter will occur. Generally, one should treat the filters as one would care for a good optical surface.

In conclusion it can be said that by means of multilayer interference coatings primary color filters suitable for additive color projection and having particular advantages over glass and gelatin have been developed. The filters offer satisfactory saturation, afford high brightness values, and are colorimetrically stable with temperature.

The authors are grateful to R. Kraft for technical assistance in the preparation of the filters, and to L. I. Epstein for theoretical contributions.

Discussion

John G. Stott (*Du-Art Film Laboratories, Inc.*): Why were not actual spectrophotometric curves of the filters shown rather than theoretical engineering curves?

Mr. Schroeder: It seemed that from the standpoint of practicability it might be more useful to show these engineering curves. They were taken directly from the experimental curves, with minor deviations eliminated. You could expect within 5% to duplicate these engineering curves. We could have shown the actual curves just as well, but the engineering curves seem more useful because in many cases you see these requirements defined in straight-line values rather than in curves.

A 35mm Stereo Cine Camera

By C. E. BEACHELL

This paper deals with the design and construction of a 35mm stereo cine camera outlining the optimum facilities required, the problems encountered in design of the camera and how they were solved, and the technique used in shooting stereo motion pictures with this camera.

A STEREO CINE CAMERA should have the following features:

1. Cameras should be rigidly mounted on the bedplate so as to withstand normal shocks encountered in use and transit without going out of calibration or synchronization.
2. Interaxial control must be possible from a minimum of approximately the physical width of the film (1.5 in.) to at least 12 in.
3. Convergence control which may be calibrated in the same manner as the focus of a lens, i.e. in feet in front of the camera, should be included. This calibration must remain accurate throughout the range of interaxial distance and preferably remain fixed as the interaxial distance is changed.
4. A binocular (stereo) viewfinder should be provided as well as the conventional flat viewfinder.
5. Shutters should be exactly synchronized with each other.
6. Camera should be removable from the carriages without loss of synchronization when replaced.
7. Motors should be provided for synchronous operation, battery operation with variable indicated frame rate and stop frame for animation work.
8. Camera must accommodate both 400- and 1000-ft magazines.
9. Weight of the camera should be kept to a minimum for ease of handling.

After considering various methods of obtaining small interaxial distance it was decided that mirrors or prisms in the optical path should not be used because:

1. They limit the use of wide-angle lenses.
2. There is loss of light in transmission thus effectively reducing lens speed.
3. A single mirror or prism produces a reverted negative image.
4. The use of 50% transmission mirrors required some color correction which means that light reaching the film is effectively less than 50% of the scene brightness.

It was decided to design this stereo camera using direct objective systems and separate negatives for left and right images. The minimum interaxial

Presented on October 8, 1953, at the Society's Convention at New York by C. E. Beachell, National Film Board of Canada, 35 John St., Ottawa, Ont., Canada.
(This paper was received Sept. 24, 1953.)

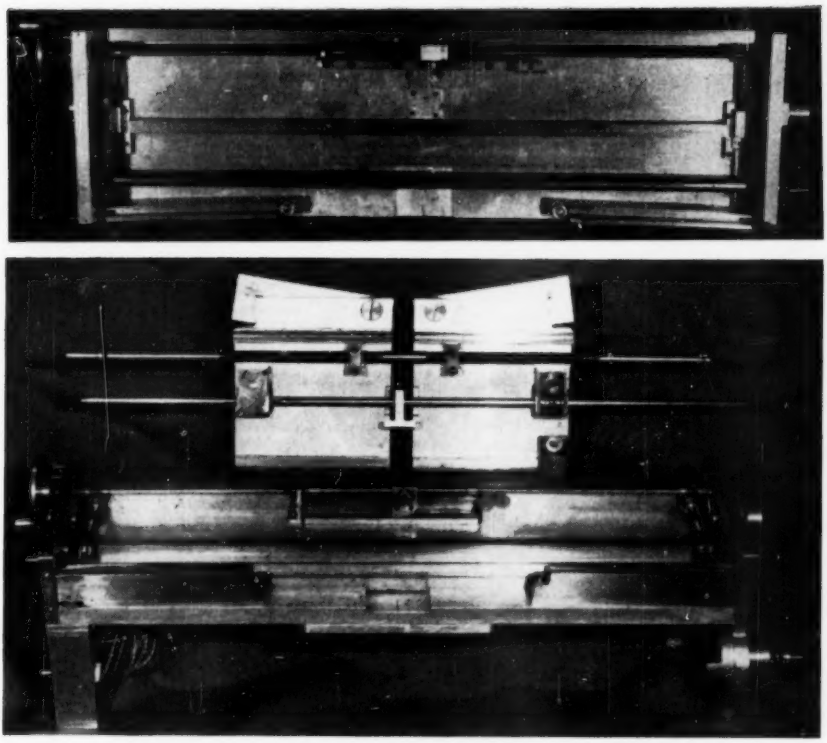


Fig. 1. Above, bedplate; below, bedplate and carriages.

distance obtainable was just under 2 in. due to the width of the films and the thickness of the camera doors. Conveniently this distance is approximately the diameter of most standard lenses which would be used on the camera.

In this camera the bedplate (Fig. 1) is cast duraluminum $\frac{3}{4}$ in. thick × 24 in. long × $7\frac{1}{4}$ in. wide. Three steel rails $\frac{1}{2}$ in. thick are inserted into the bedplate to a depth of $\frac{1}{8}$ in. The front rail is V'd on top and controls the movement of the camera carriages so that they remain parallel to each other. The center rail is for strengthening of the bed; and the rear rail, which is flat on top, supports the weight of the back of the camera carriages. Keyways are cut into the sides of the front and back rails and steel clips which are bolted to the rails of the carriage are hooked into the keyways. This arrangement prevents any lifting of the camera carriages from the rails which control their position.

On each carriage the camera mounting plate is pivoted at a point immediately under the center of the film plane and rotates about this point to control convergence (Fig. 2). The cameras are mounted and doweled on these rotor plates.

Interaxial Control

Interaxial control is achieved by means of a shaft having a right- and a lefthand thread cut in a portion of each

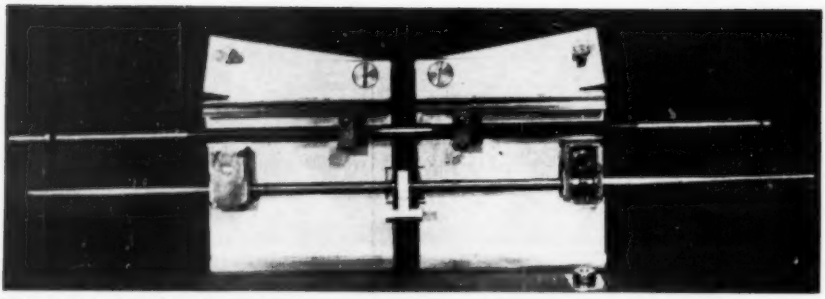


Fig. 2. Underside of carriages, showing interaxial control, main driveshaft, gearboxes and pivoted mounting plates.

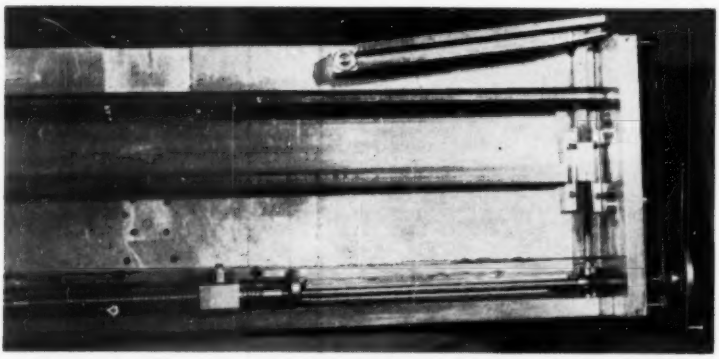


Fig. 3. Convergence control mechanism. Note angled control rail.

end of the shaft. A split nut is bolted to each carriage and engaged with the right and left threads in the lead screw respectively. Thus, when the lead screw is turned in one direction, both carriages are moved away from the center of the bedplate. By reversing the rotation of the lead screw, they are drawn together at the center. Mounted on the bedplate is a calibrated scale on which the movement of $\frac{1}{2}$ in. equals 1 in. The pointer is mounted on the back of the right-hand carriage. The range of interaxial distance is 1.95 in. to 13 in. The wider interaxial distances are used for longer lenses and for long shots with shorter lenses provided there is no resolvable information in the foreground. For example, it was found that if you shoot a subject, say, 15 ft distant from the camera and converge on the subject with a 2-in. lens and an interaxial distance of $2\frac{1}{2}$ in., then the same perception of thickness of the subject can be achieved at a distance of 30 ft using an interaxial distance of 5 in. and a 4-in. lens. Therefore, as the lens focal length is doubled, the interaxial distance must be doubled to maintain the same perception of depth or thickness.

Convergence Control

Convergence is controlled by two rails which are mounted immediately in front of the V rail (Fig. 3). These rails each pivot at a point 5 in. to the right and left respectively of the center line of the camera bed. The free ends of these rails are moved forward for convergence and backward for diver-

gence through a gearing system and two lead screws so arranged that one rotation of the control handle moves the end of the rail 0.025 in. while the convergence indicator moves 0.1 in.

A point on the rotor plate 5 in. to the right of the center of the film plane of the right camera and to the left of the left camera center is engaged with a slot in its respective control rail. These points are the control points of the rotor plates. Thus, in this arrangement the pivot points of the rotor move along a line 90° to the center line of the camera bed. The control points of the rotor plates follow a line along the control rail, thus maintaining constant convergence distance in front of the camera with negligible error throughout the full range of interaxial distance when the angle of the control rail is kept constant. This is proven by the equation:

$$\text{Max } D_c \text{ in.} - \text{Min } D_c \text{ in.} = \cot \beta - 6.5 \cot \theta \text{ (see Appendix 1)}$$

where β is minimum convergence angle and θ is maximum convergence angle, with the control rail angle constant and minimum and maximum interaxial distances in inches. A general formula for convergence angle at any interaxial distance and any angle of the control rail is given in the equation:

$$\theta = \alpha + \sin^{-1}\left[\left(\frac{I_c - 10}{10}\right) \sin \alpha\right] \text{ (see Appendix 1)}$$

when θ is the angle of convergence;
α is the angle of control rail; and
I_c is the interaxial distance in inches

The maximum convergence distance error encountered throughout the complete range of convergence and interaxial distance was found to be 1.3 in. at $3\frac{1}{2}$ ft which is actually less than the error involved in reading the calibration and therefore negligible. The maximum error at 5 ft is 0.14 in. This figure reduces as convergence distance approaches infinity where the error is 0.

This mechanism on the camera removes the necessity of making complicated calculations for convergence angle when shooting stereo cine pictures, thus saving a lot of time and reducing the probability of bad takes due to errors in calculations. Calculation for nearness and thickness factors can be made readily with the use of the Motion Picture Research Council 3D calculator.

In this camera, the silent aperture is used. Shots can be composed so that the essential picture material lies in an area suitable for 1.85:1 aspect ratio.

Development work is proceeding on a binocular viewfinder which will be mounted so that its objective systems follow faithfully all changes of the interaxial and/or convergence settings of the camera. The ocular systems provide an upright stereo picture with the same viewing angle as that of viewing a 20-ft screen from a distance of 60 ft. With this device, results of calculations may be readily verified with regard to distortions and painful background divergences. As soon as the construction of the viewfinder is completed and tested a companion paper will be submitted.

Optics

This camera is so designed that the optics are direct, thus permitting the use of conventional matched pairs of lenses from extremely short focal length, e.g. 20 mm, to telephoto. The only limiting factor in the short focal length lenses is that they must not have a physical radius greater than one-half the minimum interaxial distance at which they are to be used. The use of mirrors and prisms was avoided in design for the reasons mentioned previously.

The Driving Mechanism

The driving mechanism consists of a long shaft which runs the length of the camera bed and which has a keyway cut in the portion at each end over

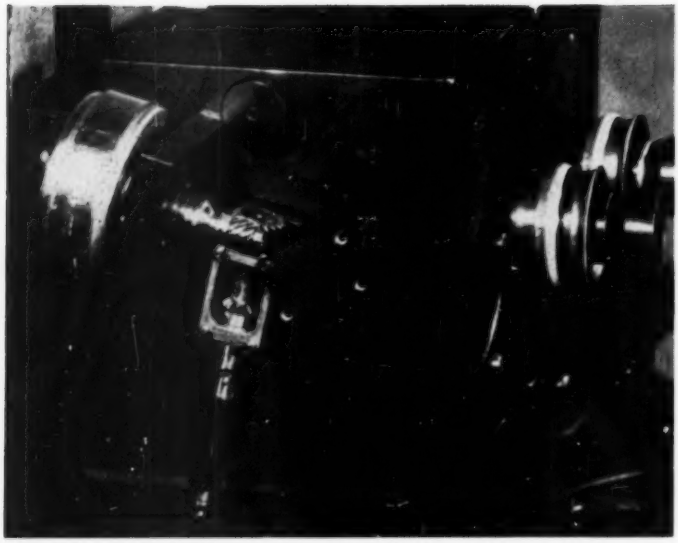


Fig. 4. Drive mechanism: telescoping shaft, gearbox and tachometer.

which the camera carriages move. This keyway drives a set of gears which have a 1:1 ratio and changes the direction of the shaft 90°; helical gears are used to avoid noise. The camera is driven through two universal joints and a telescoping shaft to a 90° 1:1 gearbox mounted on its side (Fig. 4). The universal joints and telescoping shaft accommodate the movement of the camera for convergence. The shaft from the camera gearbox then drives the camera in the conventional manner.

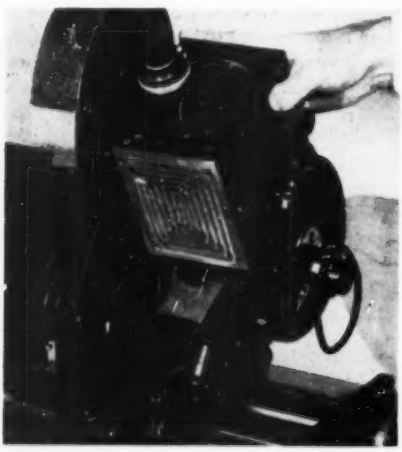


Fig. 5. Left camera lifted from rotor plate.

As this camera was an experimental project it was decided to use a pair of Bell & Howell Eyemo movements, rather than spend a large amount of money on registration movements. These were modified and one of them now is mounted upside down and runs backwards. It is planned — if stereo production demand warrants it — to install registration movements in this camera in the future, but for the present the Eyemo movements are satisfactory although somewhat noisy. To date no attempt has been made to blimp this camera as it was basically an experiment in stereoscopy.

With this type of drive it is impossible for the shutters to get out of synchronism (Fig. 5). When the cameras are removed from the rotor plate for any reason, the drive breaks at the tele-

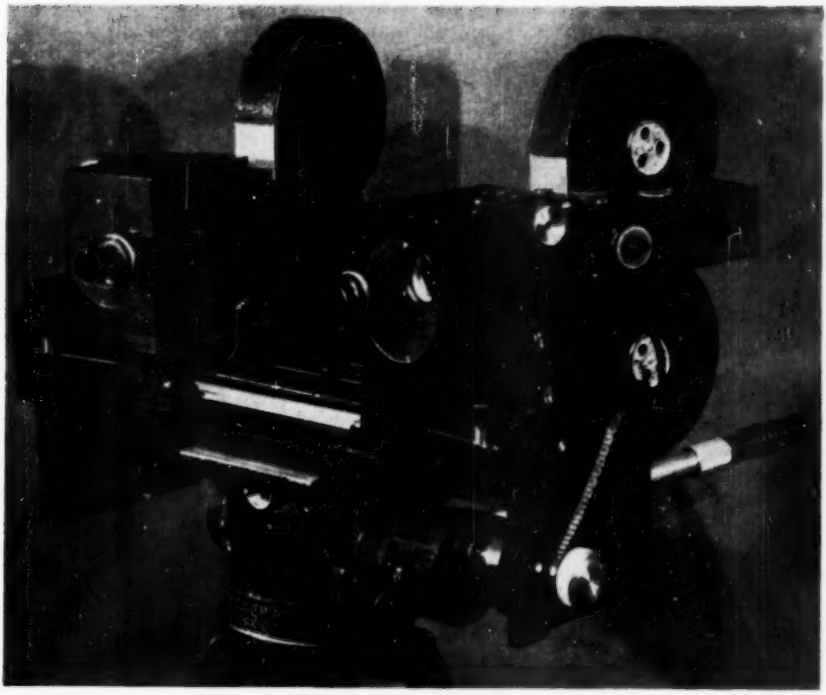


Fig. 6. General view of camera.

scoping shaft and can be reassembled only with shutters interlocked.

Takeup is driven by independently controlled motors.

Footage is indicated by a counter driven by a gearing arrangement on the end of the main driveshaft.

All controls and indicators in connection with the camera are on the right rear corner of the bed conveniently located for the camera assistant.

This prototype model camera is not equipped with a follow focus control, but, if stereo production warrants, this feature can be included without too much difficulty.

The motor mounting is a standard Bell & Howell (Fig. 6). Variable-speed battery motors or 3-phase synchronous motors can be readily used. Motor speed for 24 frames/sec is 1440 rpm. The motor is linked to the main driveshaft by a silent chain with 2:1 reduction sprockets so that the main drive rotates at 720 rpm. This slower speed was used to reduce noise. For animation work an Acme Stop Frame Motor is readily adaptable.

The camera will accommodate either 400- or 1000-ft Bell & Howell magazines. The weight of the complete camera, less magazines, is 86½ lb.

Conclusion

In stereo shooting it has been our experience that convergence should never be changed during a shot. When convergence follows a moving figure, it produces the very unlikely and somewhat disturbing effect of the set moving in and out of the theater while the actor remains on the screen. The same

effect is apparent although to a lesser degree when interaxial distance is changed and convergence remains constant. We have found that the only time either control should be moved during a shot is when the camera is either being panned or tilted. This movement covers the disturbing effect of other changes.

In this camera the following design features have been achieved:

1. Rigid mounting with complete flexibility for changes of interaxial distance and convergence.
2. Objective systems are direct, permitting the use of very wide angle lenses with full light transmission.
3. Calibrated interaxial control from 1.95 in. to 13 in.
4. Convergence control accurately calibrated in feet in front of the camera ranging from 3.5 ft to infinity. Calibration remains accurate throughout full range of interaxial distances.
5. Exact mechanical synchronization of shutters.
6. Cameras may be dismounted for routine maintenance, transportation, etc., and remounted without loss of synchronization.
7. Motors are provided for battery, synchronous and stop-frame operation.
8. 400- or 1000-ft magazines may be used on the camera.

Regardless of the future of stereo cine pictures in the entertainment field, there is a tremendous future for the medium in the instructional film field. This field of film making is our primary interest at the National Film Board of Canada.

Acknowledgments

Thanks are due to the following personnel of the National Film Board: Ken Carey, for his assistance in the design and final tests of the camera; Fred Exeter and Les Dupuis for their many helpful suggestions and work in constructing the camera bed; and Nic Culic and Wilf Sauve for their work on the camera movements.

APPENDIX

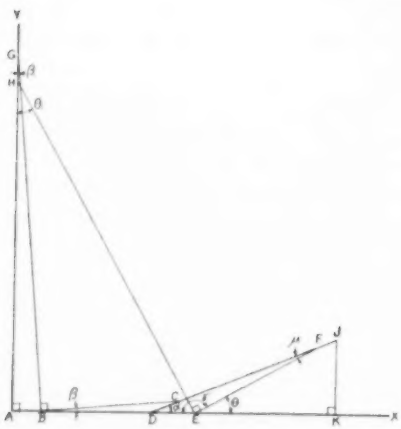


Figure 7.

Figure 7 is a geometric illustration of the right camera.

AY is the c/L of the stereo camera bed.

AX is a line in the film plane and || to the bed rails.

DJ is a line along the right control rail.

BD and EF are the positions of a line between the pivot point and the control point of the right camera pivot plate at min. and max. interaxial distance.

JK is varied to control angle α.

$AD = BC = EF = 5$ in. by construction.

$AB = 1$ in. " "

$AE = 6.5$ in. " "

$DK = 6.5$ in. " "

$DE = 1.5$ in. " "

Ic is interaxial distance.

$$DE = \frac{Ic}{2} - AD$$

To find $\angle\theta$:

In the triangle DFE

$$\frac{EF}{\sin\alpha} = \frac{DE}{\sin\mu}$$

$$\sin \mu = \frac{DE \sin \alpha}{EF}$$

$$\gamma = 180 - \left[\alpha + \sin^{-1}\left(\frac{DE \sin \alpha}{EF}\right)\right]$$

But $\gamma = 180 - \theta$

$$\therefore \quad \theta = \left[\alpha + \sin^{-1}\left(\frac{DE \sin \alpha}{EF}\right)\right]$$

But $DE = \frac{Ic}{2} - 5$ and $EF = 5$

$$\therefore \quad \theta = \alpha + \sin^{-1}\left[\left(\frac{\frac{Ic}{2} - 5}{5}\right) \sin \alpha\right]$$

$$\theta = \alpha + \sin^{-1}\left[\left(\frac{Ic - 10}{10}\right) \sin \alpha\right]$$

When $\angle \alpha$ remains constant and $\frac{Ic}{2}$ changes from AB to AE,

AG = Max. D_c
AH = Min. D_c
Dc = Distance to convergence in inches.

It can be shown that:

$$\angle \beta = \angle \beta_1$$

and

$$\angle \theta = \angle \theta_1$$

In the $\Delta\ AGB$

$$\cot\ \beta_1 = \frac{AG}{AB}$$

$$AG = AB \cot \beta_1 \qquad \text{(I)}$$

In the $\Delta\ AHE$

$$\cot \theta_1 = \frac{AH}{AE}$$

$$AH = AE \cot \theta_1 \qquad \text{(II)}$$

Subtracting (II) from (I)

$$AG - AH = AB \cot \beta_1 - AE \cot \theta_1$$

By construction:

$$AB = 1 \text{ in.} = {}^1/_2 \text{ Min. } I_c$$
$$AE = 6.5 \text{ in.} = {}^1/_2 \text{ Max. } I_c$$

$\therefore$ Max. D_c − Min. $D_c = \cot \beta - 6.5 \cot \theta$

To find JK for any $\angle \alpha$ from 0° to 7°:

In the $\Delta\ JDK$

$$\text{Tan } \alpha = \frac{JK}{DK}$$

$$JK = DK \tan \alpha$$

But $DK = 6.5$ in.
$\therefore \quad JK = 6.5 \text{ Tan } \alpha$

Projector for 16mm Optical and Magnetic Sound

By JOHN A. RODGERS

In addition to reproducing sound from conventional optical tracks, this projector is capable of recording and playing back magnetic oxide tracks applied to either single- or double-perforated 16mm films. The important aspects of the mechanical and electrical design are described, showing their relation to the performance of the projector.

SUCCESSFUL DESIGN requires a knowledge of the intended use of the product, the necessary performance characteristics and the special conditions of operation. This information must be sought out and carefully considered if the design is to prove satisfactory. Since magnetic sound is new to 16mm film projectors, the requirements are less easily determined and to some extent must be anticipated for the various users by the designers.

General Description

A projector of this type must satisfy the requirements of the conventional optical sound machine and in addition provide the means for recording and reproducing sound magnetically, preferably on all types of 16mm film. It is also essential that all operations be simple and as nearly foolproof as possible.

The compactness of the complete projector, which measures 16½ by 10½ by 12½ in. and weighs 42 lb, makes it readily portable and its power output of 7 w is sufficient for most audiences. It is installed in a durable fabric-covered case, which has a removable side that serves as a baffle for the loudspeaker. This construction is shown in Fig. 1.

Operation

The controls on the amplifier panel shown in Fig. 2 have been reduced to a minimum and grouped for ease of use. Figure 3 shows the knob controlling the positions of the record and erase heads for the three conditions of operation. In the "Optical" position both heads are away from the sound track. In the "Magnetic Play" position the record head is in contact with the track, while the erase remains away. Both heads are in contact in the "Magnetic Record" position. The metal flag attached to the control shaft prevents the operator from threading the film around the sound drum until he has moved the record and erase heads out of the way by turning to "Optical."

Optical sound film may be reproduced by setting the head control and the amplifier selector switch to "Optical" and

Presented on October 7, 1952, at the Society's Convention at Washington, D.C., by John A. Rodgers, Eastman Kodak Company, Camera Works, 333 State St., Rochester 4, N.Y.
(This paper was received Sept. 15, 1953.)

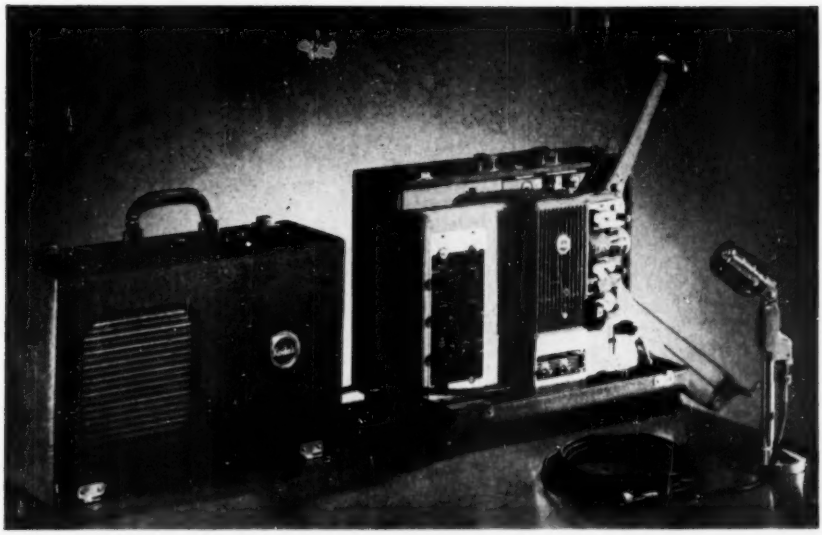


Fig. 1. Complete projector showing speaker and microphone.

operating the volume and tone controls in the usual manner. If the head control were inadvertently turned to one of the other positions, where scratching of the sound track could occur, no sound would be reproduced, since the switch on the rear of the control would disconnect the exciter lamp.

The projector amplifier may be used as a public address system when the microphone is attached and the selector switch turned to "Optical." In a similar manner a record player connected at the "Phono Input" makes use of the projector sound system.

Magnetic sound tracks may be reproduced when the head control and selector switch are turned to "Magnetic Playback." Recording is accomplished in several ways depending upon the results desired and the extensiveness of auxiliary equipment available. For voice recording the microphone is attached and the head control and selector switch set to "Magnetic Record." The volume control is adjusted so that the neon indicator flashes on peaks of the voice signal and under these conditions

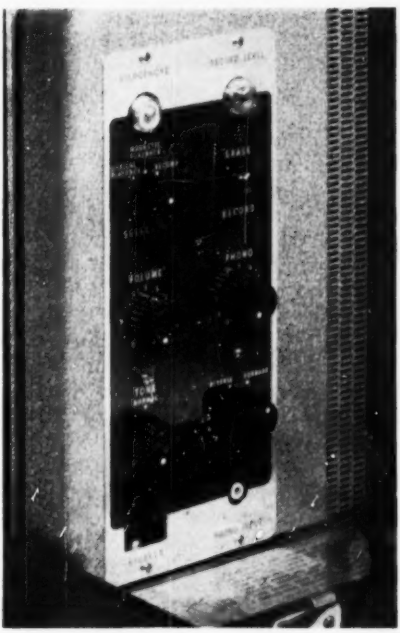


Fig. 2. Amplifier control panel.

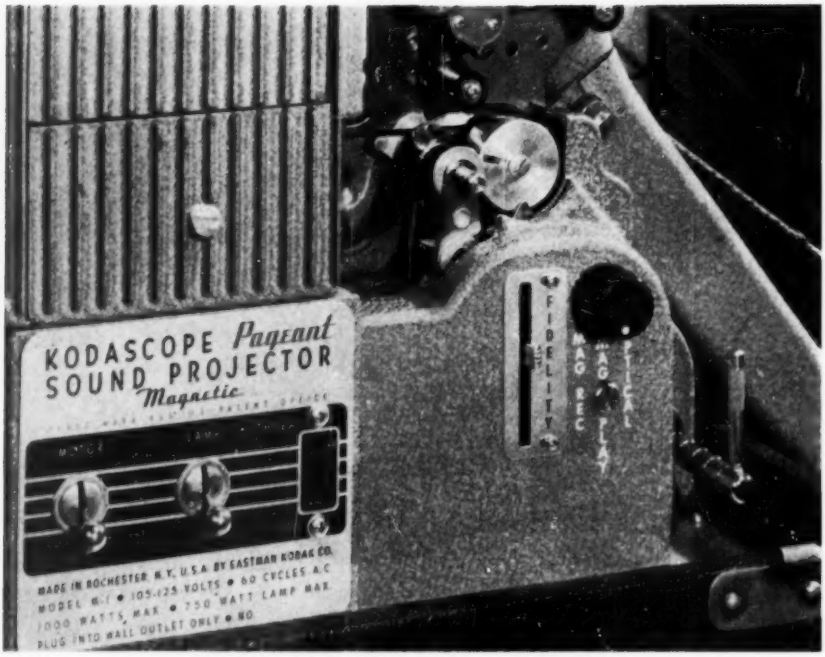

KODASCOPE Pageant
SOUND PROJECTOR
Magnetic
MADE IN ROCHESTER, N.Y., U.S.A. BY EASTMAN KODAK CO.
MODEL 8-T • 105-125 VOLTS • 60 CYCLES A.C.
1000 WATTS MAX. • 750 WATT LAMP MAX.
PLUG INTO WALL OUTLET ONLY • NO.
FIDELITY
MAG REC
MAG PLAY
OPTICAL

Fig. 3. Sound head showing control switch.

all previously recorded sound is erased from the track.

If it becomes necessary to alter a section of the recording, the projector can be reversed by means of the knob shown in Fig. 2 and the film run back to a point somewhat beyond the part to be changed, with the selector switch in the "Magnetic Playback" position. The machine is then run forward and when the section to be changed arrives, it is only necessary to return the selector switch to "Record" and proceed with the revised recording. Because the erase head is located immediately ahead of the record head, erasure is restricted to the section of track that is to be re-recorded.

Music may be recorded with the microphone placed in front of the source or it may be applied electrically by the attachment of a record player or tape recorder at the "Phono Input" socket. The signal level may then be adjusted by means of the "Phono" control as shown in Fig. 2. Since this control is independent of the master volume control, by which the microphone input level is adjusted, it is possible to mix voice and music as desired.

During recording the loudspeaker can be used for monitoring, since the recorded signal is audible but at a level sufficiently reduced to avoid coupling with the microphone. Headphones plugged into the speaker socket provide a more satisfactory method of monitoring where two or more people are engaged in making a recording involving the mixing of voices and music.

Partial Erase

An alternative method of recording divides the operation into two steps and is usually considered more convenient. In this the music and sound effects are first recorded at full level and the voice

commentary added during a second recording with the head control in the "Magnetic Playback" position. Since the erase head is not in contact with the track during the voice recording, the previously recorded music is not erased. However, it is reduced automatically to the proper level for background music.

Safety Devices

Wherever possible safety devices are incorporated so that the operator will not inadvertently damage a recorded track, but these have been designed in such a way that they do not unduly complicate the operation of the projector. The amplifier selector switch cannot be turned into the "Record" position unless the knob is partially withdrawn. This is accomplished simply by the addition of a pin at the back of the knob that interferes with a stud on the panel behind it. During recording operations this knob may be interchanged with one of the others for convenience.

When the selector switch and head control are at "Magnetic Record," the red warning light on the amplifier panel is on, indicating that magnetic tracks will be erased. The light gives additional assurance that the conditions for recording are correct. If the head control is then moved to "Magnetic Play," the warning light will be on but at a lower intensity to show that a track can be partially erased.

The record and erase heads are protected during threading by the metal flag on the head-control shaft which prevents insertion of the film until the heads are moved away. As nas also been mentioned previously the exciter lamp for optical sound reproduction remains off until the heads are removed from the film. Therefore scratching of optical sound track is virtually impossible.

To reverse the projector the reversing switch, which is equipped with a return spring, is operated and the motor started. The reversing switch can then be allowed to return to the forward position and the motor will continue to run backward until shut off because the switch operates only on the starting winding of the split-phase motor. This feature saves time and prevents mistakes by making it unnecessary for the operator to remember the reversing switch when forward motion is again required.

Amplifier Circuits

A miniature pentode (Fig. 4) provides high voltage gain for the first stage and the input is connected to the phototube, the magnetic-head transformer, and the microphone in the order of positions of the selector switch. Its output is applied to the volume control where the signal is then mixed with the signal coming from the phono-level control and applied to the second and third stages, a high-gain miniature dual triode. Next a low-gain miniature triode is used in a phase-splitter circuit to drive the push-pull output pentodes. Inverse feedback stabilizes the output stage and reduces the amplifier internal impedance. The tone control reduces the low frequencies when operated in a counter-clockwise direction from "Normal" and attenuates the high frequencies in the clockwise position. This circuit is disconnected during recording.

The oscillator supplies current to the exciter lamp for optical sound reproduction and to the erase head and bias winding for magnetic recording. It is of the Hartley type using a miniature triode and a powdered iron core coil tuned to about 40 kc. When the selector switch is turned from "Record" to "Magnetic Playback," the plate supply for the oscillator is disconnected and this part of the switching takes place a short interval ahead of the other circuit switching. A condenser connected between the oscillator plate and ground stores enough energy to cause the high-frequency current to decay over several cycles when the plate supply is switched off. This not only eliminates switching clicks in the recording but avoids possible magnetiza-

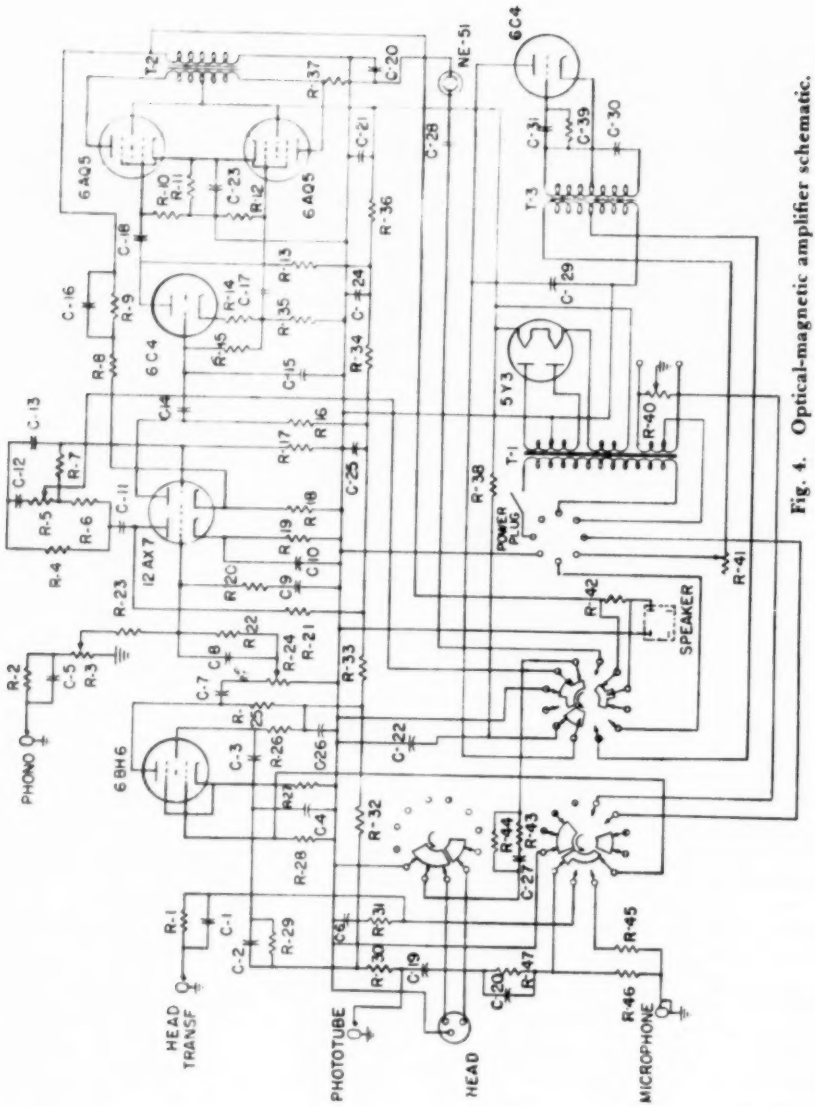


Fig. 4. Optical-magnetic amplifier schematic.

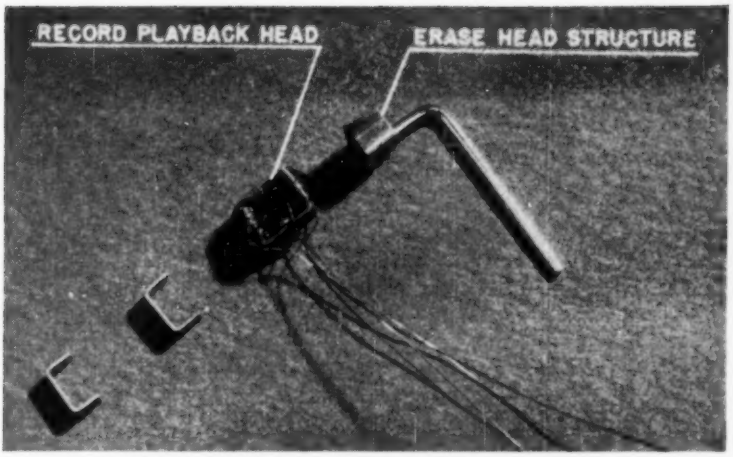


Fig. 5. Magnetic sound record and erase heads.

tion of the heads by preventing a discontinuity in the waveform of the bias current.

Magnetic Heads

The erase and record heads, shown in Fig. 5, are similarly constructed of pairs of 0.015-in. thick mu-metal U-shaped sections soldered at the front and back gaps. The front gaps are provided with copper spacers. The erase head has a 0.005-in. spacer and is 0.125-in. wide to overlap the 0.100-in. track. Since it requires only 20 coil turns, it has been found feasible to wind it after assembly.

The record-head sections are wound with 100 turns each on a special machine and then positioned in a fixture and soldered together. The spacer in the front gap is 0.0004-in. thick and the head is 0.090-in. wide. The front faces of both heads are ground and polished flat and the bias turns added to the record head prior to its installation and potting in its metal shield.

Head Mounting

Both the record and erase heads are mounted on pivoted arms (Fig. 6) actuated by a cam on the control shaft and pulled into position by coil springs. The rear of the shaft is equipped with positioning detents and a switch for controlling the warning light and the exciter lamp.

Adjustment of the erase head is obtained by provision for sliding its support arm in the sleeve on the pivoted arm and by rotating it. A set-screw at location "A" in the sleeve is then tightened to lock it in place. The actual screw does not appear in the figure.

The azimuth alignment of the record head is accomplished by loosening screws "B," which hold the shield in which the head is potted, and rotating the head to obtain a maximum signal output from a special 8000-cycle azimuth adjustment track.

Screw "C" forces a nylon pin against the record-head mounting rod and, when this is released slightly, two other adjustments can be made. Operation of screw "D" against the arm in the rod rotates the head so that it may be positioned correctly for contact across the entire width of the track. The screwdriver adjustment at "E" actuates an eccentric pin engaging a slot in the support rod to move it up and down. This permits the head gap to be placed in contact with the magnetic track.

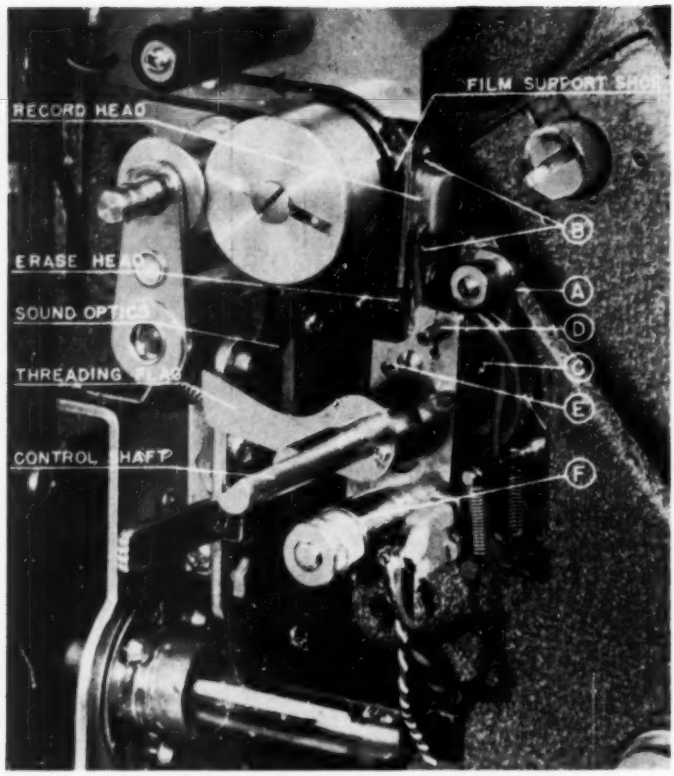


Fig. 6. Sound head with cover removed.

The head mounting arms are pivoted on a shaft threaded at the outer end for adjusting nut "F" and held away from the mounting plate by a coil spring. This nut may be turned to center the heads on the track.

Sound Stabilization

Frequency variations in the form of wow or flutter are less than 0.4% by reason of the large flywheel and the damping roller located between the sound drum and sound sprocket. Variations in the amplitude of the sound on "Magnetic" are caused by improper contact between the head gap and the track. These are of the order of 0.2 db at 1000 cycles and vary with the quality of the track itself. At higher frequencies these variations are considerably greater. It has been found that a pressure of about 1 oz is sufficient for good contact between the head and the track and that greater pressure produces no improvement in the amplitude variations but hastens the wear of the head.

Double-Perforated Film

There is an obvious need for sound recording on the double-perforated silent type of 16mm film in that it immediately opens the door to both the amateur and professional who already have film records of this type. This precludes the necessity for expensive duplicating on single-perforated sound type of film and

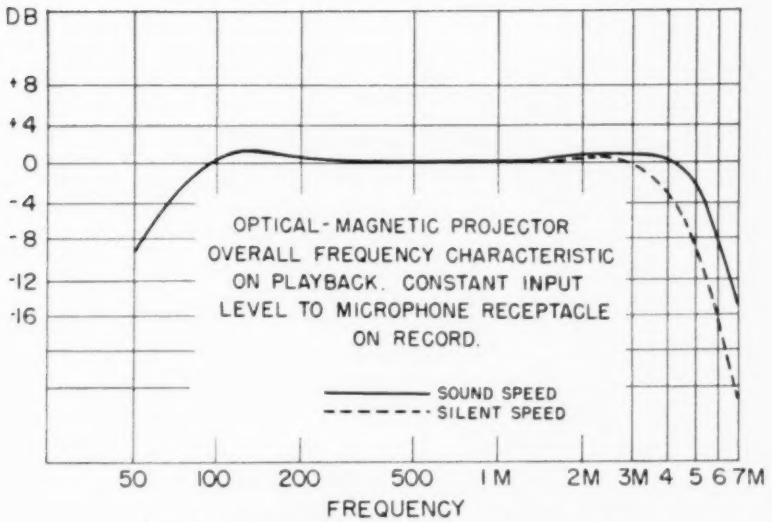


Fig. 7. Record-playback frequency characteristic.

also allows the use of any 16mm motion-picture camera. Furthermore, the projector can be operated at silent speed to suit the action in the picture and the sound will be satisfactory, although there will be some sacrifice in the high-frequency response, as can be seen in Fig. 7.

Optical sound-track scanning requires that the film project beyond the rear of the sound drum and it has been found necessary to support the film at this edge for satisfactory operation when double-perforated film with its 0.030-in. wide magnetic track is used. Therefore, a film support shoe, shown in Fig. 6, has been added. This shoe is in contact with the film at the rear edge when the record head is on the track and is effective in minimizing the sprocket-hole modulation that would otherwise result in unsatisfactory sound quality.

This provision for the operation of the projector with double-perforated film also assures improved results with distorted film and uneven magnetic tracks, where the amplitude variations would otherwise be too great for satisfactory sound.

Because of its intermittent character, speech may be recorded and played back on the double-perforated type of film with tolerable results even when no special effort has been made for reducing the sprocket-hole modulation. However, this is not the case with music, where even small disturbances in the uniformity of the sound render the quality noticeably unsatisfactory.

System Noise

The amplifier sensitivity is sufficient to afford a reserve gain of about 20 db when playing back a 0.100-in. wide magnetic-track recorder fully. This is considered necessary when it is realized that the 0.030-in. track supplies about 12 db less playback level. There are also variations in output from tracks applied by different manufacturers.

With such high sensitivity in the amplifier the problem of keeping the noise down to a tolerable level becomes difficult and extreme care must be observed to prevent the stray fields from the motor and power transformer from coupling with the amplifier circuits, input transformer, head and cables.

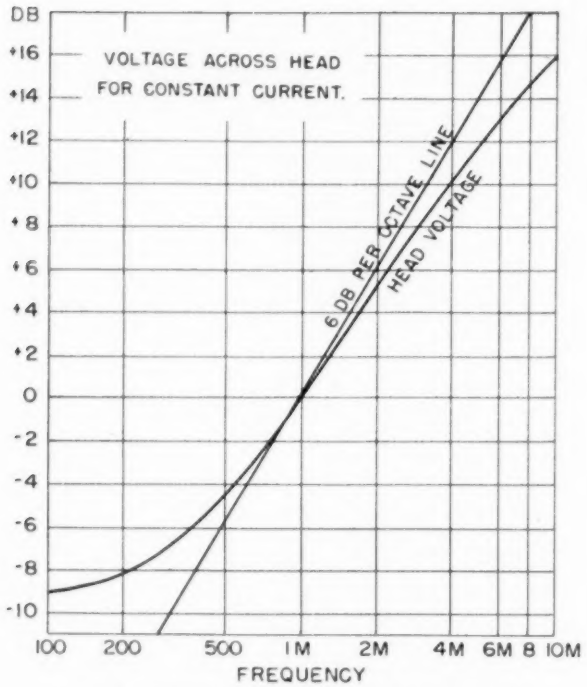


Fig. 8. Record-head frequency characteristic.

The record head is enclosed in a shield and the lead wires from it are tightly twisted. Additional shielding is used on the input transformer and this is mounted in back of the sound head and separated from the amplifier by properly placed shields. A signal-to-noise ratio of over 40 db is obtained, comparing a fully recorded to an erased track.

Frequency Response

The overall frequency-response curves are shown in Fig. 7. These were obtained by recording from an audio oscillator with a constant-voltage input at the microphone socket and measuring the output on playback across a dummy load resistor connected at the speaker socket.

The overall characteristics of the magnetic sound shown in Fig. 7 are determined by the frequency response of the amplifier for both recording and playing back. The results of tests indicate the desirability of recording with nearly constant current in the recording head over the frequency range. The mu-metal recording head exhibits losses at the high frequencies, however, that require compensation in the amplifier. In Fig. 8 will be seen a curve of the voltage across the head throughout the frequency range when it is supplied constant current by means of a series resistor. The departure from a straight line indicates these losses and they are compensated for by raising the amplifier gain the appropriate amount in this region. Actually it has been found desirable to provide a small additional rise at both the high and low frequencies, as this reduces the compensation necessary on playback. The result is less hiss and hum. If these

rises are too great, however, there will be a tendency to over-record, with resulting distortion on playback. The departure from the straight line at the low-frequency end of the curve is caused by resistance in the head winding, which remains nearly constant while the reactance decreases as the frequency is reduced. The response of the amplifier on playback relative to 1000 cycles shows a rise of 15 db at 100 cycles and a drop of 1 db at 7000 cycles.

One of the important problems concerning magnetic recording is the selection of the electrical frequency-response characteristics for both recording and playing back. Since the two complement each other to produce an overall frequency response, an infinite number of combinations exist and standardization becomes necessary if films recorded on one projector are to be satisfactorily reproduced on a machine of different manufacture. This is a problem that has already caused concern to the manufacturers of tape-recording equipment where wide variations exist in these characteristics.

The work now being done by the Magnetic Recording Subcommittee is therefore important and will ultimately provide a satisfactory solution to this problem of standardization.

Acknowledgments

Assistance in the design of this projector has been given by H. N. Fairbanks, L. T. Askren and A. N. Ringler, along with helpful suggestions by many others.

Discussion

J. G. Frayne (Westrex Corp.): I notice that the author uses the term "optical" throughout the paper to designate the photographic track. There has been a concerted effort in the 35mm field to use the term "photographic" rather than optical and it is therefore a matter of regret that in the 16mm projector field the term optical seems to be widely adopted.

Gordon A. Chambers, Chairman of the Session (Eastman Kodak Co.): It certainly shows that the work of one of the subcommittees of the Society on a glossary of terms is long overdue.

E. W. D'Arcy (De Vry Corp.): I would like to inquire whether you would state what the post-equalization is in your particular projector.

Mr. Rodgers: I did not show any curves for that. That is one of our biggest problems. On this particular projector, the playback electrical characteristic in the amplifier is such that relative to 1000 cycles 100 cycles is raised about 15 db and the 7000-cycle point is down about 1 db.

W. E. Youngs (International Motion Picture Service, U.S. Dept. of State): What provision do you have for a music and sound effects track when an optical track and a magnetic track are being played at the same time?

Mr. Rodgers: That cannot be done on this machine because the input is switched either to the photographic sound record, or to the magnetic. It might be possible to combine the two and I can see where on foreign language prints the sound effects and music could be put on the photographic sound record and then the voice recorded on the magnetic. This would make it possible to change the language without altering the sound effects. Does that answer your question?

Mr. Youngs: Yes, it does. Now, another thing, in a previous paper I think the Film Board of Canada was talking about two languages recorded on two tracks placed side by side on a variable-area or similar system. Have you worked out any separation system on that, for cutting down, say, half the area?

Mr. Rodgers: That can be done, but then it would be necessary to mask off a section of the optical system so as to reproduce only one at a time. That can be done quite easily.

German Test Film

The D. K. G. Test Film No. 4a, produced by the German Motion-Picture Engineering Society in Munich, is intended as a means for making routine listening and viewing tests in the theater and for checking projector performance. No additional equipment, other than a stopwatch, is required.

Contents

The film consists of a number of tests whose nature is indicated by subtitles as follows:

Clock Ticks. The volume control should be set so that the ticking is just audible and not changed again for the duration of the test.

Projection Rate. A stopwatch is shown running for one minute. Running time should be checked against another stopwatch and the result compared with Table I. Variations from the normal may indicate that adjustments to the film-drive mechanism are necessary.

Picture Placement. This test consists of five concentric lines placed parallel to the edges of the picture, at intervals equal to 1% of standard picture size (Fig. 1). Discrepancies up to 5% of standard picture size can thus be detected. In the center of the vertical and horizontal lines are stepped wedges which will indicate jump and weave in percent.

D. K. G.-Prüffilm Nr. 4a produced by Deutsche Kinotechnische Gesellschaft E.V., München 2, Thorwaldsenstrasse 9/11, Germany.

Test for Travel Ghost. Heavy horizontal lines with crossbars and lettering in the center of the frame permit observation to determine whether the shutter is correctly adjusted (Fig. 2). Should the shutter be in need of adjustment the lines will appear to be distorted vertically and blurred.

Table I.

Normal time in sec	Time shown on film in sec	Frames/sec	
60	50	28.8	fast
60	52	27.7	"
60	54	26.7	"
60	56	25.7	"
60	58	24.8	"
60	**60**	**24**	**normal**
60	62	23.2	slow
60	64	22.5	"
60	66	21.8	"
60	68	21.2	"
60	70	20.6	"

Resolution. A concentric grid fills the entire picture, with numbered axes and diagnals, a central star and four surrounding stars (Fig. 3). The surrounding stars should be in almost as sharp focus as the central star.

Typical Scene. This picture is intended to serve as a general test for screen brightness and quality of reproduction.

During the projection rate test, following some recorded speech, three piano chords are struck as a test of flutter. Both speech and music should be clear and free from distortion.

Figure 1

Figure 2

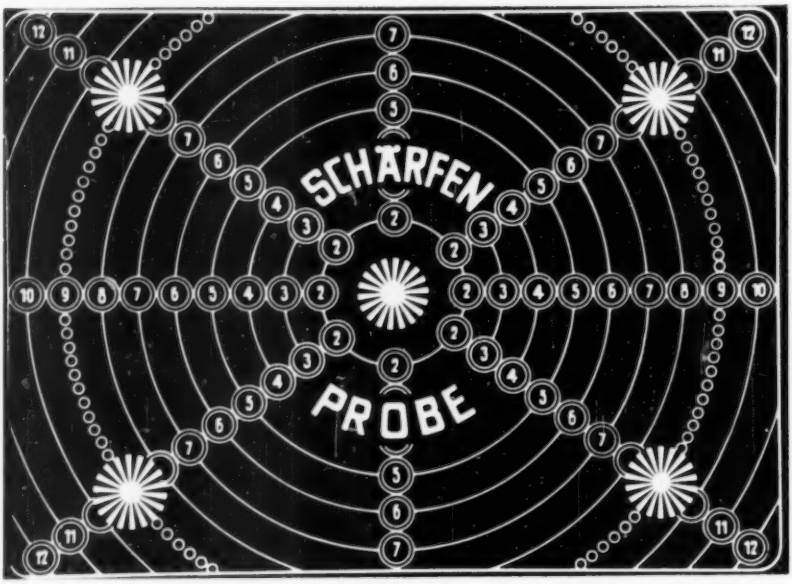


Figure 3

Two Revised American Standards

PH22.43, –.44—16 mm Sound Test Films

REVISIONS of two American Standards on 16mm sound test films have been approved by the American Standards Association and are published on the following pages.

In accord with the periodic review procedures of the ASA, these two standards were reviewed by the SMPTE Sound Committee in March 1951. No fundamental changes were proposed. There is a minor revision of the section "Resistance to Shrinkage." This revision generalizes the method of measuring shrinkage whereas a particular (and now outmoded) method of the National Bureau of Standards was specified previously. In addition, the titles of the Standards have been simplified and made consistent with current practice.—*Henry Kogel*, Staff Engineer

AMERICAN STANDARD

16mm 3000-Cycle Flutter Test Film

ASA
Reg. U.S. Pat. Office
PH22.43-1953
(Revision of Z22.43-1946)
*UDC 778.55

1. Scope and Purpose

1.1 This specification describes a 3000-cycle sound test film for use in determining the presence of flutter in 16mm sound motion-picture projectors.

2. Test Film

2.1 Recording. The test film shall have either an originally recorded, direct-playback positive variable-area sound track or an originally recorded variable-density sound track developed as a toe record. The recorded frequency shall be within ± 25 cycles of the nominal 3000-cycle frequency. The modulation of the recording shall be 80 ± 5%. The output level of the film shall be constant within ± 0.25 db. (This is equivalent to an amplitude tolerance of ± 0.0015 inch when recording variable-area sound track with a nominal amplitude of 0.055 inch.) The recording shall be accomplished in a recorder so constructed as to keep the flutter content to the absolute minimum consistent with the state of the art. The total rms flutter content of the film shall be less than 0.1% upon shipment by the test film manufacturer. The waveform distortion of the recording shall not exceed 5%.

2.2 Film Stock. The film stock used for the test film shall be cut and perforated in accordance with the American Standard Cutting and Perforating Dimensions for 16-Millimeter Sound Motion Picture Negative and Positive Raw Stock, Z22.12-1947, or the latest revision thereof approved by the American Standards Association, Incorporated.

2.2.1 Resistance to Shrinkage. The film stock used for the test film shall have a maximum lengthwise shrinkage of 0.50% when tested as follows: At least 20 strips of film approximately 31 inches in length shall be cut for measurement of shrinkage. After normal development and drying (not over + 80 F (+ 26.7 C)), the strips shall be placed at least ¼ inch apart in racks and kept for 7 days in an oven maintained at + 120 F (+ 49 C) and a relative humidity of 20%. The strips shall then be removed, reconditioned thoroughly to 50% relative humidity at + 70 F (+ 21.1 C), and the shrinkage measured by a suitable method. The percent shrinkage shall then be calculated on the basis of deviation from the nominal dimension for the length of 100 consecutive perforation intervals given in American Standard Z22.12-1947, or the latest revision thereof.

2.3 Standard Length of Film. The standard length of the flutter test film shall be 380 ft.

2.4 Leader and Trailer. Each test film shall be furnished with a suitable leader, title and trailer.

Note: A test film in accordance with this standard is available from the Society of Motion Picture and Television Engineers.

Approved October 26, 1953, by the American Standards Association, Incorporated
Sponsor: Society of Motion Picture and Television Engineers
*Universal Decimal Classification

Copyright 1953 by the American Standards Association, Incorporated
Printed in U.S.A.
ASA½M1053
Price, 25 Cents

AMERICAN STANDARD

16mm Multifrequency Test Film

ASA
Reg. U.S. Pat. Office
PH22.44-1953
(Revision of Z22.44-1946)
*UDC 778.55

1. Scope and Purpose

1.1 This standard describes a multifrequency sound test film used for testing and adjusting the sound systems of 16mm sound motion-picture projection equipment. The test frequencies on this film are adequate for normal field and general laboratory use.

2. Test Film

2.1 Frequencies. The test film shall contain the following series of frequencies, each preceded by spoken announcement recorded at approximately 10 db below full modulation:

Frequency, cycles	Tone Footage, feet	Frequency, cycles	Tone Footage, feet
400	12	2000	6
50	6	3000	6
100	6	4000	6
200	6	5000	6
300	6	6000	6
500	6	7000	6
1000	6	400	12

2.1.1 Frequency Tolerance. The frequency tolerance of the recorded signals shall be ± 2% of the nominal frequency of each portion of the test track.

2.2 Recording. The test film shall be an originally recorded, splice-free, direct playback, positive variable-area sound track, recorded so that the modulated light is substantially constant when the film is reproduced with a scanning beam of negligible width. Modulation of the recording shall be 95 ± 5% at 7000 cycles. The level within any one frequency of each reel shall be constant to within ± 0.5 db. The recording shall be accomplished on a recorder so constructed as to keep the flutter content of the film to the absolute minimum consistent with the state of the art. The distortion of the recorded wave, up to a frequency of 3000 cycles, shall not exceed 5%.

2.3 Film Stock. The film stock used for the test film shall be cut and perforated in accordance with the American Standard Cutting and Perforating Dimensions for 16-Millimeter Sound Motion Picture Negative and Positive Raw Stock, Z22.12-1947, or the latest revision thereof approved by the American Standards Association, Incorporated.

2.3.1 Resistance to Shrinkage. The film stock used for the test film shall have a maximum lengthwise shrinkage of 0.50% when tested as follows: At least 20 strips of film approximately 31 inches in length shall be cut for measurement of shrinkage. After normal development and drying (not over + 80 F (+ 26.7 C)), the strips shall be placed at least ¼ inch apart in racks and kept for 7 days in an oven maintained at + 120 F (+ 49 C) and a relative humidity of 20%. The strips shall then be removed, reconditioned thoroughly to 50% relative humidity at + 70 F (+ 21.1 C), and the shrinkage measured by a suitable method. The percent shrinkage shall then be calculated on the basis of deviation from the nominal dimension for the length of 100 consecutive perforation intervals given in American Standard Z22.12-1947, or the latest revision thereof.

2.4 Film Identification. Each test film shall be provided with a suitable leader, title and trailer, and shall be accompanied by a calibration of the level of the frequency recordings.

2.4.1 Calibration. The calibration shall be in terms of light modulation at the photocell with a scanning beam of negligible width, and shall be correct to within ± 0.25 db up to and including 3000 cycles, and within ± 0.5 db above 3000 cycles up to and including 7000 cycles. The correction for each frequency shall be so stated that it will give the true level when the correction is added algebraically to the output level measured using the film.

Note: A test film in accordance with this standard is available from the Society of Motion Picture and Television Engineers.

Approved October 26, 1953, by the American Standards Association, Incorporated
Sponsor: Society of Motion Picture and Television Engineers

*Universal Decimal Classification

Copyright 1953 by the American Standards Association, Incorporated

Printed in U.S.A.
ASA½M1053

Price, 25 Cents

75th Convention Plans

Nearly two years ago the Board of Governors appointed a special committee under John G. Frayne, to make the 75th a special milestone convention. The first meeting of this committee was held during the Chicago Convention; subsequent meetings and correspondence have enabled Chairman Frayne to submit for the forthcoming Washington Convention the following roster of papers which will consider the developments of facets of the industry and will also be basic and tutorial in nature:

"Black-and-White Cinematography" — C. E. K. Mees, Eastman Kodak Co.
"Color Cinematography" — Gerald F. Rackett, Columbia Pictures Corp.
"Sound" — E. W. Kellogg, RCA Victor Div. (Ret.)
"Professional 35mm Camera" — C. E. Phillimore, Bell & Howell
"16mm Projector and Camera" — M. G. Townsley, Bell & Howell
"Evolution of Motion-Picture Techniques" — James Card, Eastman House
"Motion-Picture Lighting" — Charles Handley, National Carbon Co.
"35mm Projector" — R. Mathews, Los Angeles County Museum; and Willy Borberg, General Precision Laboratory
"Mechanical Television" — J. V. L. Hogan, Consultant
"Electronic Television" — A. G. Jensen, Bell Telephone Laboratories
"The Motion-Picture Laboratory" — John I. Crabtree, Eastman Kodak Co.
"The Evolution of Motion-Picture Theaters" — Ben Schlanger, Theater Consultant

There will be a few additions to this list — but generally this is the frame of the 75th Program.

The papers listed above will be substantial papers of about an hour's length. To these will be added briefer papers about current developments in the industry. These papers are now being sought and arranged by the Papers Committee listed below. If you have a prospective paper or know about one, bring it to the attention of the Committee member nearest you.

W. H. Rivers, *Chairman*, Eastman Kodak Co., 342 Madison Ave., New York 17, N. Y.
Joseph E. Aiken, *Program Chairman*, 116 N. Galveston St., Arlington 8, Va.
Skipwith W. Athey, *Vice-Chairman*, General Precision Laboratory, 16 South Moger Ave., Mt. Kisco, N. Y.
C. E. Heppberger, *Vice-Chairman*, 231 N. Mill St., Naperville, Ill.
G. G. Graham, *Vice-Chairman*, National Film Board of Canada, John St., Ottawa, Canada
Ralph E. Lovell, *Vice-Chairman*, National Broadcasting Co., Sunset and Vine, Hollywood 28, Calif.
John H. Waddell, *Vice-Chairman*, Wollensak Optical Co., 850 Hudson Ave., Rochester 21, N.Y.

Papers Committee Members

James A. Anderson, Alexander Film Co., Alexander Film Bldg., Colorado Springs, Colo.
Mark Armistead, 1041 N. Formosa Ave., Hollywood 46, Calif.
D. Max Beard, Naval Ordnance Laboratory, White Oak, Silver Spring, Md.
Edward E. Bickel, Simpson Optical Manufacturing Co., 3208 W. Carroll Ave., Chicago 24, Ill.
Richard Blount, General Electric Co., Nela Park, Cleveland, Ohio
R. P. Burns, Balaban & Katz, Great States Theaters, 177 N. State St., Chicago 1.
Merle H. Chamberlin, Metro-Goldwyn-Mayer Studios, 10202 Washington Blvd., Culver City, Calif.
P. M. Cowett, Dept. of the Navy, Bureau of Ships, Washington 25, D.C.
E. W. D'Arcy, De Vry Corp., 1111 W. Armitage Ave., Chicago 14, Ill.
W. H. Deacy, Jr., 231 E. 76 St., New York 21, N.Y.
W. P. Dutton, 732 N. Edison St., Arlington 3, Va.
Barry T. Eddy, 10569 Selkirk Lane, Los Angeles, Calif.
Carlos H. Elmer, 410B Forrestal St., China Lake, Calif.

Karl Freund, 15024 Devonshire St., San Fernando, Calif.

Jack R. Glass, 10858 Wagner St., Culver City, Calif.

R. N. Harmon, Westinghouse Radio Stations, Inc., 1625 K St., N.W., Washington, D.C.

Scott Helt, Allen B. Du Mont Laboratories, Inc., 2 Main Ave., Passaic, N.J.

S. Eric Howse, 2000 West Mountain St., Glendale 1, Calif.

L. Hughes, Hughes Sound Films, 1200 Grant St., Denver, Colo.

P. A. Jacobsen, Campus Studios, 100 Meany Hall, University of Washington, Seattle, Wash.

William Kelley, Motion Picture Research Council, 1421 N. Western Ave., Hollywood 27, Calif.

George Lewin, Signal Corps Pictorial Center, 25-11—35 St., Long Island City 1, N.Y.

Glenn E. Matthews, Research Laboratory, Eastman Kodak Co., Rochester 10, N.Y.

Pierre Mertz, Bell Telephone Laboratories, Inc., 463 West St., New York 14.

Harry Milholland, Du Mont TV Network, Station WABD, 515 Madison Ave., New York 22.

W. J. Morlock, General Electric Co., Electronics Park, Syracuse, N.Y.

Herbert W. Pangborn, 6512 Orion St., Van Nuys, Calif.

Bernard D. Plakun, General Precision Laboratory, Inc., 63 Bedford Rd., Pleasantville, N.Y.

Carl N. Shipman, 9544 Burma Rd., Rivera, Calif.

S. P. Solow, Consolidated Film Industries, Inc., 959 Seward St., Hollywood 38, Calif.

J. G. Stott, Du-Art Film Laboratories, 245 W. 55 St., New York 19.

W. L. Tesch, Radio Corporation of America, RCA Victor Div., Front & Cooper Sts., Camden, N.J.

Lloyd Thompson, The Calvin Co., 1105 Truman Rd., Kansas City 6, Mo.

M. G. Townsley, Bell & Howell Co., 7100 McCormick Rd., Chicago 45, Ill.

Allan L. Wolff, Westrex Corp., 6601 Romaine St., Hollywood 38, Calif.

Roy L. Wolford, 3434 W. 110th St., Inglewood 2, Calif.

74th Semiannual Convention

The Society's Fall Convention was held at the Statler Hotel, New York, during the week October 5–9. Registration was 632, of which 90 were ladies' registrations.

The following, in addition to respective officers of the Society, were responsible for Convention arrangements:

Program, Skipwith W. Athey

Papers, W. H. Rivers, Joseph E. Aiken, Geo. W. Colburn, G. G. Graham, Charles Jantzen, Ralph E. Lovell and John H. Waddell

Local Arrangements, W. H. Offenhauser, Jr., R. C. Holslag and S. L. Silverman

Hotel Reservations and Transportation, L. E. Jones

Hospitality, Marie Douglass

Luncheon and Banquet, Emerson Yorke, J. B. McCullough and J. G. Stott

Membership and Subscriptions, A. R. Gallo

Motion Pictures, V. J. Gilcher

Projection, William Hecht and Charles Muller

Public Address, George Costello and Dominick Lopez

Publicity, Leonard Bidwell

Registration, J. C. Naughton

Ladies Program, Mrs. Emerson Yorke and Mrs. Herbert Barnett

The motion-picture shorts shown at the beginning of the various sessions included:

Marciano-La Starza Fight, Republic Pictures

SMPTE Roundup, Emerson Yorke Studio

Let's Ask Nostradamus, M-G-M

Illusions Unlimited, National Broadcasting Company

Excerpts from foreign-language training films, Signal Corps Pictorial Center

TV of Tomorrow, M-G-M

Little League World Series, Emerson Yorke Studio

Hurricane Hunters, Paramount

The Nature of Polarized Light, Polaroid Corp.

A is for Atom, General Electric Company

Madeline, Columbia

A complete listing of the sessions and

papers will be published in the December *Journal*. Attendance during technical sessions generally ranged from 85 to 110, with one special high of 255 during the Thursday Evening 3-D Equipment Session.

As principal speaker at the Get-Together Luncheon, Henry J. Taylor, radio commentator, gave a survey of international political developments. President Barnett, in his address, spoke as follows:

Get-Together Luncheon Remarks by President Barnett

". . . Twice each year for the past 37 years, members of the Society and leaders from every branch of our allied industries have met in a national convention that has grown in size from eleven men to the vast registration of the last two conventions. With size has come strength, importance and responsibilities. Each convention has advanced the theory and practice of engineering in motion pictures, high-speed photography, and more recently in television, and the related arts and sciences.

"The practical missions of our conventions are not accomplished by passive attendance. You will not fulfill your duty to yourself, your company, and to our industries solely by listening to informative discussions by authorities in your fields. You must be more than a mental sponge absorbing technical knowledge. This is a market place where the costly lessons of research and experience can be acquired for the price of asking questions. This is a meeting of minds—minds that know and minds that *want* to know. This is a get-together of productive people with ideas and imagination and an insatiable curiosity about the things they suspect lie beyond the horizon.

"In addition to technical benefit to be derived, there are other rewards for your participation in the common cause of a better product. The Society expects each one of you to use this opportunity to strengthen the bonds within the industry. This is the time to renew old acquaintances; to turn business associates from other parts of the country into friends; the chance to meet the men whose names until now were bylines in technical journals.

"In all of these ways you will contribute to the strength and the progress of the motion picture and the television industries. And when the last session ends on Friday, you will leave here enriched in mind and spirit with the knowledge that our engineers have the ability and will to contribute their share in keeping the film industry a vital, dynamic part of the American economy.

"There is one lesson above all others which you should learn this week. You are *never* working alone. Right behind you, ready to help you over the big obstacles, ready to share with you their hard-earned knowledge, are nearly 5,000 engineers and scientists who voluntarily work together as the Society of Motion Picture and Television Engineers. Available to you in the *Journal* and other publications is the most comprehensive source of motion-picture technical information in the world, as well as for certain aspects of television. The potential value of this knowledge to our related industries depends upon the use you make of it and to the degree you contribute to it in recording new discoveries.

"We are now in the most competitive era the motion picture has ever known. Losses of the past few years have been tragic, especially to the small independent exhibitor. Aside from the personal misfortunes this has brought, it is serious to the industry as a whole. We fully realize the small contribution made by community theaters to the total gross boxoffice of any production. There is, on the other hand, a much greater service these houses perform in shaping the movie-going habits of the American audience. This, I think, is a challenging problem deserving of most serious consideration.

"Out of the adversities of the past has come a reawakening which shows promise of restoring motion pictures to an important economic position. This is particularly gratifying to our Society in that the industry has seen the value in drawing on the technical resources long waiting to be used. We are doubly grateful that these resources were available. Whether or not any of these, or all, may show the way back, we know that it is unwise to lapse again into a feeling of false security. As important as the techniques may be which have been introduced over the past year, no industry on earth is rich enough to waste them on selling otherwise unsalable merchandise. Furthermore, the industry cannot expect

these devices to carry them forever. Our long range salvation depends on how well we have learned from the past few years and to the degree we apply every segment of the industry to a most thorough study of its needs and responsibilities to the paying audience.

"The engineer has today an excellent opportunity to contribute worthwhile advances to a receptive industry. I am sure you are prepared to meet this challenge."

For the first time since the 68th Convention at Lake Placid, an evening session was given over to the presentation of awards. The record of the citations will be given in the December *Journal*.

The Ladies Program included a visit to the U.N. Headquarters, a special showing of old-time motion pictures at the Museum of Modern Art, and attendance at a performance of *The Robe*.

There were 13 meetings of the various Engineering Committees held during the course of the Convention. Results of such meetings are published from time to time in the *Journal* as reports by committee chairmen and in the Engineering Activities column. At the Papers-Editorial meeting there was detailed discussion about ways to get papers best published in the *Journal* and about Papers Committee operation for the 75th Convention. The latter subject is covered in a separate story in this *Journal*.

Book Review

The Theory of Stereoscopic Transmission and Its Application to the Motion Picture

By Raymond Spottiswoode and Nigel Spottiswoode. Published (1953) by The University of California Press, Berkeley 4, Calif. 200 pp. 32 illus. + 6 pp. 3-D illus. 6 × 9 in. $6.00.

This volume is the first full-scale treatment of the problems of stereoscopic transmission. On this score alone it is a great contribution to the art which should be required reading for the technicians of those producers who have been willing to film and exhibit stereoscopically inferior pictures — which, to date, means substantially all of them.

In order to cast the volume in its proper light, it is necessary to examine its basic philosophy. It tacitly assumes that if two retinal images are produced in the eyes of the observer which exactly reproduce those that would have been received from the original scene, the observer will then interpret them in exactly the same manner. Since the authors are well aware that such reproduction is not completely possible, their procedure is to develop the mathematics of this ideal supposition, analyzing the effects of inevitable departures along the way. The result is a highly formulated mathematical treatment.

The attack is analytical and equational rather than geometric. Of course the equations are derived from the geometry of the situation, but the conclusions are in general extracted from the equations rather than from geometric figures as in many instances they might well have been. Though the procedure renders the results more rigorous, it is somewhat unfortunate for the general reader who usually is not in the habit of tracing through mathematical formulae but can quite readily follow geometric figures because of their greater recognizable visual content. On this score the reader will do well to be constantly aware of the stereoscopic diagrams in anaglyph form enclosed in the back cover. One could have wished, however, for a more liberal use of explanatory figures.

I also find the derivations unnecessarily long, causing the reader to become too immersed in detail. Each derivation need not have been carried through every step. For instance, on p. 24, seven equations are given in order to obtain an equation giving the distance from the observer to the stereoscopic image point. Since the mathematics is a simple similar triangle manipulation, it would seem to me to have been a better procedure simply to state that "from fig. 4 by the use of similar triangles the following equation can be derived," giving only the end result. Such a consistent reduction of the mathematical manipulations throughout the book would have freed the reader to pay more attention to the important results.

Though the authors do an excellent job of calling attention to the limitations of the mathematical approach, I find my own misgivings far exceed theirs. They slip occasionally into translating stereoscopic image formation into spectator interpretation as though the latter inevitably followed. For instance, on p. 34 in discussing the separation of infinity points on the screen the following statement appears: "(2) B zero·N will be zero. Thus points originally at infinity will appear to the spectator at infinity." This implicitly assumes that the spectator interprets what he sees as he should. A more careful statement would have been ". . . Thus points originally at infinity will be viewed with eye axes parallel."

Certainly their treatment is basic and necessary, but the variables are numerous and the psychological factors of such great importance that I feel that the ideal stereoscopic motion picture will only be arrived at through empirical study of audience reactions to controlled alteration of the variables. Thus it is well to know how to produce a stereoscopic image which is theoretically ortho-stereoscopic for a single, centrally located viewer, but such an image in the long run is in itself of no importance. Ultimately we are not interested in reality but in the artistic and aesthetic effect of stereoscopic image patterns on audiences. We are interested in producing a piece of sculpture which has a high artistic impact rather than in reproducing exact forms through technical skill. Thus I doubt very seriously that motion-picture producers will ever make great use of the mathematical approach, but will depend on gradually blocking out in broad terms the areas of operation which minimize eyestrain and maximize favorable audience reaction. This will be achieved by empirical experimentation with image shapes.

On the technical side I feel that the authors make too little distinction between absolute convergence and relative convergence. It seems to me that the evidence is that absolute convergence is of very little importance — that is, the location of a stereoscopic image as a whole, assuming the existence of a completely dark theater where no external reference points exist (an impossibility, of course) does not depend on convergence. However the image is fixed, once it has been fixed, the internal location of points depends to a very high degree on relative convergence and mathematics comes into its own.

The importance of this point becomes apparent in considering separations of infinity point-pairs greater than the human interocular. In earlier papers of my own I considered such separations bad practice because I assumed that eyestrain would result. Recent experiments on this point seem to indicate clearly that the eyes can diverge through a small angle (which amounts to a large one from the stereoscopic viewpoint) without eyestrain. By doing so the two retinal images obtained from two pictures on the screen with infinity points separated by six inches are exactly the same as they would be if the pictures were separated by the human interocular and the eye axes remained parallel. The interpretation of the relative positions of internal points will probably be the same in both cases, but where is the image as a whole in the first case? Where is the image as a whole when a stereo pair placed side by side in a book is fused by divergence without the aid of lenses or filters?

In spite of the fact that theater reference points or screen texture are always present, the location of images as a whole seems to me to depend much more heavily on psychological factors than do the relationships of internal points.

The above is not meant as a criticism of this excellent and much needed volume but only as a word of caution on the way. We know very, very little about the interpretive mechanisms of vision. The worker in this field should consider this volume a real "must" but should always maintain a wholesome, objective doubt of all reasoned, calculated results unless there is conclusive evidence that they have been empirically verified by a number of observers.

Outside of the mathematical passages, the writing is unfortunately not as clear or precise as it might be. Also, in their efforts to cover every phase of stereoscopic transmission, the authors often give almost equal emphasis to trivia and fundamentals, so that a reader could get a discouraging impression of the complexity of the subject.

On a minor key. The alternate-frame

camera shown in Fig. 22, p. 105, has an error not pointed out by the authors. The path of the right-eye picture is longer than that of the left eye by a distance of *tc*, say 2½ in. Thus a similar double-lens camera would have one lens 2½ in. in back of the other—a bad situation for close objects.

Unfortunately the printing is quite inferior. The letter separation within a single word is sometimes irregular to the point of having the appearance of two words.

The authors are to be congratulated for the completeness of the book. They have ferreted out many obscure points that have never before reached the literature. Certainly no one else has approached the field with their degree of thoroughness.—*John T. Rule*, Massachusetts Institute of Technology, Cambridge 39, Mass.

New Members

The following members have been added to the Society's rolls since those last published. The designations of grades are the same as those used in the 1952 MEMBERSHIP DIRECTORY.

Honorary (**H**) Fellow (**F**) Active (**M**) Associate (**A**) Student (**S**)

Moore, James Whitney, Editor, Movie Makers, Managing Director, Amateur Cinema League, Inc., 420 Lexington Ave., New York 17, N.Y. (**A**)

Neilis, Frank A., Jr., Television Projectionist, Du Mont Television Network. **Mail:** 3914 Avenue I, Brooklyn 10, N.Y. (**A**)

Norman, Harry H., Mechanical Engineer, Zig Zag Machine Co. **Mail:** 15235 Valley Vista Blvd., Sherman Oaks, Calif. (**A**)

Nosti, Benigno, Head, Film Dept., Circuito CMQ, S.A., M St. #312, Vedado, Havana, Cuba. (**A**)

O'Donnell, William C., Sales, Kollmorgen Optical Corp., 347 King St., Northampton, Mass. (**A**)

Ostrowski, Wallace W., Film Technician, Color Corporation of America. **Mail:** 244 North California St., Burbank, Calif. (**A**)

Palmer, Merrill A., Project Photographer and Recorder, Lovelace Foundation for Medical Education and Research. **Mail:** 2312 Rice Ave., N.W., Albuquerque, N.M. (**A**)

Pasqualetti, Bev J., Instructor, In Charge, Dept. of Photography, City College of San Francisco. **Mail:** 78 San Jacinto Way, San Francisco 27, Calif. (**A**)

Patton, Billy L., Electrical Engineer, WJAR-TV. **Mail:** 58 Merritt Rd., Riverside, R.I. (**A**)

Pennington, Harry, Jr., Television Films. **Mail:** 134 East Agarita St., San Antonio 12, Tex. (**M**)

Petito, Vincent Arthur, Motion-Picture Equipment Repair, U.S. Army Signal Corp. **Mail:** 171 Nostrand Ave., Brooklyn 5, N.Y. (**M**)

Reitz, Lewis P., Jr., Electrical Engineer, Hughes Aircraft Co. **Mail:** 700 Mexico Pl., Palos Verdes Estates, Calif. (**M**)

Rodgers, John A., Electrical Engineer, Camera Works, Eastman Kodak Co., 333 State St., Rochester 4, N.Y. (**M**)

Rose, Ernest D., Film Producer, Owner, Trans-Lingual International Film Service, Eagle-Lion Studios, Hollywood 46, Calif. (**A**)

Ruark, Henry C., Jr., Professor, c/o Audio-Visual Center, Indiana University, Bloomington, Ind. (**A**)

Salerno, Anthony, Photographic Chemist, Pavelle Color, Inc. **Mail:** 104-69—48 Ave., Corona, N.Y. (**M**)

Schardin, Hubert, Scientific Director, Laboratorie de Recherches; Professor, University of Freiburg. **Mail:** Rosenstrasse 10, Weil am Rhein, Baden, Germany. (**M**)

Schober, Edwin E., Still and Motion-Picture Photographer, Fresno Bee. **Mail:** 324 North Fresno, Fresno, Calif. (**A**)

Schweiger, Arthur F., Maintenance Engineer (Audio and Video), National Broadcasting Co. **Mail:** 135 Sylvia La., New Hyde Park, Long Island, N.Y. (**M**)

Serbolov, Vladimiro de Berner, Supervisor, Engineer, Deksa, S.A. **Mail:** Av. Veracruz #73, Mexico 11, D.F., Mexico. (**A**)

Shurcliff, William A., Physicist, Polaroid Corp. **Mail:** 19 Appleton St., Cambridge, Mass. (**M**)

Siegel, Burt, Film Technician, Cameraman, Editor. **Mail:** 5240 Broadway, New York, N.Y. , (**A**)

Smith, Lloyd A., Executive, Eastman Kodak Co., Kodak Park, Rochester, N.Y. (**M**)

Smoot, M. Graham, Coordinator, Visual Health Education, Texas State Department of Health, 410 East Fifth St., Austin, Tex. (**M**)

Spinrad, Leonard, Consultant on Motion Pictures, 511 E. 20 St., New York 10, N.Y. (**M**)

Steglich, Kurt, Mathematician, Askania-Werke AG, Bundesallee 86-89, Berlin-Friedenau, Germany. (**M**)

Steuer, Walter, Mechanical Engineer, Vice-President, Zoomar, Inc., 55 Sea Cliff Ave., Glen Cove, Long Island, N.Y. (M)

Stork, John, Project Engineer, Altec Lansing Corp., 9356 Santa Monica Blvd., Beverly Hills, Calif. (M)

Stuart, A. J., Jr., Motion-Picture Engineer, Baptist Foreign Mission Board, 2037 Monument Ave., Richmond, Va. (A)

Stuart, James Leslie, Chief Engineer, George Humphries & Co., Ltd., 71 Whitfield St., London, England. (A)

Surette, William E., Jr., Development Engineer, Synthetic Vision Corp. **Mail:** 821 Valley St., Dayton 4, Ohio. (A)

Taylor, Herbert B., Transmission Engineer, Walt Disney Productions. **Mail:** 1520 Bel Aire Dr., Glendale 1, Calif. (A)

Thomasson, Frank, Sound Engineer, Rowley United Theatres, Inc., 314 South Harwood, Dallas, Tex. (A)

Tottenhoff, John P., Salesman, Watland. **Mail:** 930 South Lincoln, Park Ridge, Ill. (A)

Townsend, James Harvey, Jr., Vice-President and Chief Engineer, Unifilms, Inc., 146 E. 47 St., New York, N.Y. (M)

Traub, Alan C., Research Physicist, American Optical Co., Southbridge, Mass. (A)

Tucker, Guillermo, Manager, Radio Caracas TV, Barcenas A Rio, Caracas, Venezuela. (M)

Van Dyke, Willard, Cameraman, Affiliated Film Producers, Inc., 164 E. 38 St., New York 16, N.Y. (A)

Watson, H., University of California at Los Angeles. **Mail:** 115 Monterey Blvd., Hermosa, Calif. (S)

Wells, Gerald, Sr., Camera and Projector Servicing. **Mail:** 74 East Chalmers Ave., Youngstown, Ohio. (A)

Werner, Friedrich, Physicist, Member, Board of Directors, Askania-Werke, 88 Bundesallee, Berlin-Friedenau, Germany. (M)

Wessel, Karl H., Chief Engineer, Oxford Electric Corp. **Mail:** 4892 North Mason Ave., Chicago 30, Ill. (M)

Westing, John C., Sound Engineer, DeFrenes Co. **Mail:** 21 South Farragut St., Philadelphia 39, Pa. (A)

Westphal, William H., Raw Stock Sales, W. J. German, Inc. **Mail:** 224 Hamilton Rd., Ridgewood, N.J. (M)

Whiteside, Duncan, Director of Radio-TV, University of Mississippi, University, Miss. (A)

Whitley, Eric G., Product Design Engineer, Allen B. DuMont Laboratories, Inc. **Mail:** Apt. 32-G, 160 Gordonhurst Ave., Upper Montclair, N.J. (A)

Widmayer, William L., Assistant Head, Camera Dept., Columbia Pictures Corp. **Mail:** 5340 Teesdale Ave., North Hollywood, Calif. (A)

Wiley, Gerald L., Air Force Motion-Picture Camerman, U.S. Air Force, 1st Photo Squadron, 200 King St., Alexandria, Va. (A)

Williams, John B., Sound and Projection Engineer, Army and Air Force Motion-Picture Service. **Mail:** European Motion-Picture Service, APO 807, U.S. Army, c/o Postmaster, New York, N.Y. (A)

Wilson, Albert, Motion-Picture Director, Signal Corps Pictorial Center. **Mail:** 3086—33 St., Long Island City 2, N.Y. (M)

Woodruff, George N., Physicist, Reaction Motors, Inc., Rockaway, N.J. (M)

Woodruff, Rodger L., Technical Supervisor, KRON-TV, 901 Mission St., San Francisco, Calif. (M)

Yearwood, Taylor C., Projectionist, Wometco Theatres. **Mail:** 6401 N.W. Miami Pl., Miami 38, Fla. (A)

Young, Jerry O. W., Sales Engineer, Worsco Audio Dept., Sound Engineer, Snazelle Studio. **Mail:** 1420 Pacific Ave., San Francisco, Calif. (A)

Ziller, Robert, Student, Projectionist, Fox Theatre. **Mail:** 1037 North 31 St., Billings, Mont. (A)

Zuidema, John W., Product Engineer, Film Testing, Eastman Kodak Co. **Mail:** 465 Colebrook Dr., Rochester 17, N.Y. (A)

CHANGES IN GRADE

Badmaieff, Alexis, (A) to (M)
Bennett, Norman, (S) to (A)
Blaskiewicz, John V., (S) to (A)
Chamberlin, Merle H., (M) to (F)
Dearing, L. M., (M) to (F)
Drew, Russell O., (M) to (F)
Elmer, Carlos H., (M) to (F)
Fogelman, Ted, (A) to (M)
Gardenhire, Hervey, (A) to (M)
Gillette, Frank N., (M) to (F)
Graham, Gerald G., (M) to (F)
Groves, George R., (A) to (M)
Hallows, Raymond L., Jr., (S) to (A)
Halprin, Sol, (M) to (F)
Lazell, Robert C., (S) to (A)
Loughren, Arthur V., (M) to (F)
Lovell, Ralph E., (M) to (F)
Miller, Arthur J., (M) to (F)
Mosser, Adrian T., (S) to (A)
Nuttall, Howard T., (A) to (M)
Servies, John W., (M) to (F)
Soltys, Richard J., (S) to (A)
Spottiswoode, Raymond J., (M) to (F)
Townsend, Charles L., (M) to (F)
Veal, T. G., (M) to (F)

DECEASED

McInnes, Harold W., 6560 East Hastings St., North Burnaby, British Columbia. (A)

Rodrigues, R. T., Manager, Kodak, Ltd. **Mail:** Rua Garrett 33, Libson, Portugal. (M)

New Products

Further information about these items can be obtained direct from the addresses given. As in the case of technical papers, the Society is not responsible for manufacturers' statements, and publication of these items does not constitute endorsement of the products.

This film reader has been designed with a $10^1/_2 \times 10$ in. screen. It is a portable table model with the film carriage located near table level to minimize the operator's fatigue. Interchangeable lenses provide magnifications of $7^1/_2$ to 14, with other magnifications available by special order. There are interchangeable 35 mm and 16 mm film carriages. Special carriages to suit comparator work and other applications are available from D-H Instrument Co., P.O. Box 205, Station A, Palo Alto, Calif.

A new series of *f*/1.8 Super-Cinephor projection lenses designed to produce maximum brightness, contrast and sharpness, edge-to-edge, on all types of professional motion-picture screens is announced by the Bausch & Lomb Optical Co., Rochester 4, N.Y. These lenses are intended to lessen the problem of resolution at the outer margins of the screen and to increase the illumination, distributing it evenly.

These new lenses employ five different types of glass, two of which are varieties of extra dense barium crown glass, recently put on a production basis in the Bausch & Lomb glass plant. They are said to combine the optical advantages of both flint and older types of crown glass, without the disadvantages of either, and are designed to eliminate color absorption and transmit the full color and brightness of the image.

SMPTE Lapel Pins

The Society has available for mailing its gold and blue enamel lapel pin, with a screw back. The pin is a ½-in. reproduction of the Society symbol — the film, sprocket and television tube — which appears on the *Journal* cover. The price of the pin is $4.00, including Federal Tax; in New York City, add 3% sales tax.

Employment Service

These notices are published for the service of the membership and the field. They are inserted for three months, at no charge to the member. The Society's address cannot be used for replies.

Position Available

Technical Photographer, age 27 to 38, for senior position with large California industrial research organization. Should be conversant with contemporary techniques for recording data; acquainted with microscopy, graphic arts and color processes. Job involves application of photographic techniques as experimental tool in research projects. Administrative experience helpful. Excellent career opportunity for an ingenious and inventive person. Retirement pension and other benefit plans. Application held in strict confidence. Write giving personal data, education and experience to Henry Helbig and Associates, Placement Consultants, Examiner Bldg., 3d and Market Sts., San Francisco 3, Calif.

Position Wanted

Engineer, B.M.E.: Creative designs, product improvement. Photographic and electronic-mechanical fields. Cameras (film, image-orthicon and iconoscope TV cameras), color film processing, production tooling, radar. Simple constructions, pleasing appearance. Special product or production blueprints. Write J. Rafalow, Selden, N.Y.

Meetings

The American Society of Mechanical Engineers, Annual Meeting, Nov. 29–Dec. 4 Statler Hotel, N.Y.

Society of Motion Picture and Television Engineers, Central Section Meeting, Dec. 10 (tentative), Chicago, Ill.

American Institute of Chemical Engineers, Annual Meeting, Dec. 13–16, St. Louis, Mo.

American Institute of Electrical Engineers, Winter General Meeting, Jan. 18–22, 1954, New York

National Electrical Manufacturers Assn., Mar. 8–11, 1954, Edgewater Beach Hotel, Chicago, Ill.

Radio Engineering Show and I.R.E. National Convention, Mar. 22–25, 1954, Hotel Waldorf Astoria, New York

Optical Society of America, Mar. 25–27, 1954, New York

75th Semiannual Convention of the SMPTE, May 3–7, 1954, Hotel Statler, Washington

American Institute of Electrical Engineers, Summer General Meeting, June 21–25, 1954, Los Angeles, Calif.

Acoustical Society of America, June 22–26, 1954, Hotel Statler, New York

Photographic Society of America, Annual Meeting, Oct. 5–9, 1954, Drake Hotel, Chicago, Ill.

76th Semiannual Convention of the SMPTE, Oct. 18–22, 1954 (next year), Ambassador Hotel, Los Angeles

77th Semiannual Convention of the SMPTE, Apr. 17–22, 1955, Drake Hotel, Chicago

78th Semiannual Convention of the SMPTE, Oct. 3–7, 1955, Lake Placid Club, Essex County, N.Y.

SMPTE Officers and Committees: The roster of Society Officers and the Committee Chairmen and Members were published in the April *Journal*.

Society of Motion Picture and Television Engineers

40 West 40th Street, New York 18, N. Y., Tel. LOngacre 5-0172
Boyce Nemec, *Executive Secretary*

OFFICERS
1953–1954

President
Herbert Barnett, 10 East 52d St., New York 22, N. Y.
Executive Vice-President
John G. Frayne, 6601 Romaine St., Hollywood 38, Calif.
Past-President
Peter Mole, 941 N. Sycamore Ave., Hollywood 38, Calif.
Editorial Vice-President
N. L. Simmons, 6706 Santa Monica Blvd., Hollywood 38, Calif.
Convention Vice-President
John W. Servies, 92 Gold St., New York 38, N. Y.
Secretary
Edward S. Seeley, 161 Sixth Ave., New York 13, N. Y.

1952–1953

Engineering Vice-President
Henry J. Hood, 343 State St., Rochester 4, N. Y.
Financial Vice-President
Frank E. Cahill, Jr., 321 W. 44 St., New York 18, N. Y.
Treasurer
Barton Kreuzer, RCA Victor Div., Bldg. 15, Camden, N. J.

GOVERNORS
1952–1953

J. E. Aiken, 116 N. Galveston St., Arlington 3, Va.
F. G. Albin, 241 So. Wetherly Dr., Beverly Hills, Calif.
Geo. W. Colburn, 164 N. Wacker Dr., Chicago 6, Ill.
E. W. D'Arcy, 7045 No. Osceola Ave., Chicago, Ill.
J. K. Hilliard, 2237 Mandeville Canyon Rd., Los Angeles 24, Calif.
A. G. Jensen, Bell Telephone Labs., Inc., Murray Hill, N. J.

1953

C. E. Heppberger, 231 N. Mill, Naperville, Ill.
William H. Offenhauser, Jr., River St. and Charles Pl., New Canaan, Conn.
Vaughn C. Shaner, 6706 Santa Monica Blvd., Hollywood, Calif.

1953–1954

F. E. Carlson, General Electric Co., Nela Park, Cleveland 1, Ohio
Gordon A. Chambers, 343 State St., Rochester 4, N. Y.
L. M. Dearing, Drawer 791, Hollywood 28, Calif.
William A. Mueller, 4000 W. Olive Ave., Burbank, Calif.
Charles L. Townsend, 49 Hillcrest Dr., Dumont, N. J.
Malcolm G. Townsley, 7100 McCormick Rd., Chicago 45, Ill.

BOARD OF EDITORS

Chairman
Arthur C. Downes, 2161 Niagara Dr., Lakewood 7, Ohio

D. Max Beard
G. M. Best
G. R. Crane
H. E. Edgerton
C. H. Elmer
C. R. Fordyce
L. D. Grignon
A. M. Gundelfinger
C. W. Handley
A. C. Hardy
C. R. Keith
G. E. Matthews
Pierre Mertz
C. D. Miller
J. A. Norling
H. W. Pangborn
B. D. Plakun
R. T. Van Niman
J. H. Waddell
D. R. White
C. W. Wyckoff

Sustaining Members

OF THE

SOCIETY OF MOTION PICTURE AND TELEVISION ENGINEERS

Alexander Film Co.
Altec Companies
Ansco
C. S. Ashcraft Mfg. Co.
Audio Productions, Inc.
Bausch & Lomb Optical Co.
Bell & Howell Company
Bijou Amusement Company
Buensod-Stacey, Inc.
Burnett-Timken Research Laboratory
Byron, Inc.
The Calvin Company
Century Projector Corporation
Cineffects, Inc.
Cinéma-Tirage L. Maurice
Geo. W. Colburn Laboratory, Inc.
Color Corporation of America
Consolidated Film Industries
DeLuxe Laboratories, Inc.
De Vry Corporation
Du-Art Film Laboratories, Inc.
E. I. du Pont de Nemours & Co., Inc.
Eastman Kodak Company
Max Factor, Inc.
Federal Manufacturing and Engineering Corp.
Fordel Film Laboratories
General Electric Company
General Precision Equipment Corp.
- Ampro Corporation
- Askania Regulator Company
- General Precision Laboratory, Incorporated
- The Hertner Electric Company
- International Projector Corporation
- J. E. McAuley Mfg. Co.
- National Theatre Supply
- The Strong Electric Company

W. J. German, Inc.
Guffanti Film Laboratories, Inc.
Hunt's Theatres
Hurley Screen Company, Inc.
The Jam Handy Organization, Inc.
Kollmorgen Optical Corporation
Lorraine Carbons
March of Time
J. A. Maurer, Inc.
Mecca Film Laboratories, Inc.
Mitchell Camera Corporation
Mole-Richardson Co.
Motiograph, Inc.
Motion Picture Association of America, Inc.
- Allied Artists Productions, Inc.
- Columbia Pictures Corporation
- Loew's Inc.
- Paramount Pictures Corporation
- Republic Pictures Corp.
- RKO Radio Pictures, Inc.
- Twentieth Century-Fox Film Corp.
- Universal Pictures Company, Inc.
- Warner Bros. Pictures, Inc.

Movielab Film Laboratories, Inc.
National Carbon Company
- A Division of Union Carbide and Carbon Corporation

National Cine Equipment, Inc.
National Screen Service Corporation
National Theaters Amusement Co., Inc.
Neighborhood Theatre, Inc.
Neumade Products Corp.
Northwest Sound Service, Inc.
Polaroid Corporation
Producers Service Co.
Projection Optics Company, Inc.
Radiant Manufacturing Corporation
Radio Corporation of America, RCA Victor Division
Reid H. Ray Film Industries, Inc.
Raytone Screen Corp.
Reeves Sound Studios, Inc.
S.O.S. Cinema Supply Corp.
SRT Television Studios
Shelly Films Limited (Canada)
The Stancil-Hoffman Corporation
Technicolor Motion Picture Corporation
Terrytoons, Inc.
Theatre Holding Corporation
Titra Film Laboratories, Inc.
United Amusement Corp., Ltd.
Wenzel Projector Company
Westinghouse Electric Corporation
Westrex Corporation
Wilding Picture Productions, Inc.
Wollensak Optical Company